METALLOGRAPHY
APPLIED TO
SIDERURGIC PRODUCTS

HUMBERT SAVOIA

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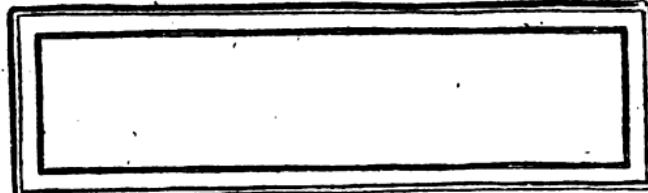
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METALLOGRAPHY

APPLIED TO

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(AWARDED A PRIZE BY THE ROYAL LOMBARD INSTITUTE
OF SCIENCE AND LITERATURE)

BY

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TRANSLATED BY

R. G. CORBET

WITH 94 ILLUSTRATIONS

TO

PROFESSOR LOUIS GABBA

WITH

GRATEFUL AFFECTION

TRANSLATOR'S PREFACE

In several connections, notably when compiling for
the Board of Trade a French-English glossary of
designations of workpeople, I have found that literal
renderings of a foreign term, or even the equivalents
given by technological dictionaries, are often quite
different from the expressions used in this country ;
experts, themselves, sometimes disagree as to these,
for a word current in one town is often unknown in
another. A result not unfamiliar to those in the
trades involved may be obtained by consulting persons
connected with them ; and the present translation has
accordingly been revised in the light of information
they have furnished, and of that gathered by reading
papers and discussions by specialists.

Besides the difficulties inherent in the highly
technical character of this work, there were others
caused by peculiarities in the style, which necessitated
occasional alterations, to make the author's meaning
clearer to the reader. This has been done as little
as possible, the aim throughout being faithful repro-

duction rather than elegance. Some changes in idiom have, of course, been unavoidable, and careful attention has been given to free the text from anomalies. Some may have escaped me, and for these, as for any other shortcomings, I crave the reader's indulgence.

I need add little as to the merits of the work; but what has struck me, on comparing it with other writings on the subject, is that it is more up to date than most of those available, and is rendered especially useful by its detailed practical directions.

R. G. CORBET.

January 1910.

PREFACE

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ITALIAN chemists and technical men, when attempting
to carry out metallographic processes, have hitherto
been obliged to read a large number of works in order
to glean from them the few fundamental notions of
which the practical worker stands in need. This
undertaking is not always feasible in the limited time
at the disposal of those engaged in manufacture.

Whilst numberless methods are alluded to, more-
over, in the many publications, chiefly foreign, that
deal with the subject, the particulars given are com-
paratively meagre, as too minute explanations con-
cerning the manual part of operations would scarcely
be called for in a theoretical treatise.

Many have, therefore, been obliged to forego metal-
lography for want of leisure, others were baffled by
the extent of the subject and the number of methods ;
others, again, after going so far as to attempt experi-
ments, have been discouraged by the uselessness of
these trials, for which they lacked the practical know-
ledge not given them by books.

Being convinced of this, Signor CHARLES VAN-
ZETTI, C.E., who had long before bought a perfect

metallographic microscope, suggested to Professor LOUIS GABBA, in 1906, the sending of a technical man to Paris, the centre of metallographic investigation, on purpose to familiarise himself with it and with its applications.

Prof. Gabba put the Author in communication with Signor Vanzetti, who commissioned him to go to Paris and begin his researches under the guidance of M. POURCEL, C.E., the famous metallurgist of Terrenoire, the first, moreover, to prepare products containing manganese in a blast-furnace, and to introduce and explain their use in steel foundries.*

The authoritative support of M. Pourcel rendered possible an extremely profitable course of study in the laboratories of HENRY LE CHATELIER † at the Collège de France and the Ecole Supérieure des Mines. The Author received, at the same time, valuable theoretico-practical lessons from CHARLES FRÉMONT, the great authority on mechanical tests of resistance and the inventor of the most perfect modern machines for gauging it.

Afterwards, through the courtesy of M. GUILLET, C.E.,‡ Director of Laboratories at the De Dion-Bouton

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* The London *Iron and Steel Institute* has recently awarded M. Pourcel the Bessemer Medal, the highest award of merit in metallurgical science.

† Member of the Institute of France since 1907, and Moissan's successor at the Sorbonne in the Chair of General Chemistry.

‡ Now Professor of Metallurgy at the Conservatoire National d'Arts et Métiers.

Works, and with the kind permission of the MARQUIS
DE DION himself, he was able for several weeks to
frequent these laboratories, in which theory and prac-
tice have reached the latest developments. Here he
watched the application of the methods examined in
Professor Le Chatelier's laboratories, their practical
importance, and the manner of employing them so
as constantly to test the output of a metallurgical
workshop.

At the close of these investigations in Paris, Signor
Vanzetti employed the Author to fit up a metallo-
graphic laboratory at the Milan Steelworks, and, thanks
to the abundant means placed at his disposal, the
latter was able to make it really complete.

He has thought it necessary to record these facts
in order to explain the origin of this handbook, which,
the publisher and himself believe, will furnish scientists
in producing workshops and building yards with the
chief notions concerning metallurgy, in a plain and
brief form.

The existing bibliographical materials have been
epitomised: one method of preparation, among many,
has been chosen, and the attempt has been made to
explain it in its most minute details, with the help of
the practice which the Author has had so many oppor-
tunities of acquiring.

As regards the descriptive portion, those parts
have been chosen, among the large numbers available,
which experience has shown to be most useful, and

those questions which most often come before practical men.

Hence this work is confined to siderurgic products, and even in this field certain subjects are fully treated, owing to their capital importance, others are briefly explained, it being considered sufficient to give a summary idea of them, and at every point the choice and extent of chapters is governed by their greater or less practical importance.

In order to make the handbook easier to read, the illustrations, as far as possible, have been placed near the letterpress concerning them. For the same reason some of them have been repeated, when the text referred to them more than once, in order to save the reader the trouble of looking for them.

The photographs of metals are all the Author's own, and he has singled out all those which show the more frequent and more characteristic aspects of the preparations, so that they may easily serve for comparison with the appearances presented to the student by his own microscope.

It is hoped that this modest work, notwithstanding its small dimensions, may contribute to the diffusion of the principles of this important method of investigation.

HUMBERT SAVOIA, C.E.

MILAN : *April* 1909.

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METALLOGRAPHY

CHAPTER I.

HISTORICAL NOTES.

FOR a long time the theoretical and practical study of the properties of metals was almost entirely confined to the domain of analytical chemistry.

Later on, the rough experiments made from time immemorial led to systematic investigation into mechanical properties, which were gradually distinguished from one another, with the aid of special apparatus, and brought under control.

It was observed that metals used for practical purposes often occasion unforeseen phenomena, manifested in considerable variations of resistance, sufficient to throw doubt upon every theoretical prevision.

Typical instances of such phenomena were breakages in the axles of vehicles, in parts of machinery, in tools, or in vessels submitted to pressure. These were comprehensible when grave defects of construction

were met with in the broken piece, or when the accident could be attributed to the indefinite repetition of mechanical action; but often none of these explanations held good, since breakages would take place in new pieces, which, on examination, showed no organoleptic defect whatever.

Chemical analysis was sometimes able to throw complete light on the subject, revealing the existence of harmful elements, such as sulphur or phosphorus in steel. But in many cases it only made the phenomenon more strange, showing absolute identity of composition between a metal that had given occasion to breakages and another from which excellent results had been obtained.

Hence the diffusion and improvement of the mechanical tests of resistance could not be relied upon as a constant aid and complement to chemical analysis, but served merely as a check and a comparison, since the frequent repetition of experiments multiplied the anomalies observed in the behaviour of metals.

From this state of affairs it followed that, while producers used analysis freely to examine raw material, the consumers of finished articles trusted solely to mechanical tests.

On the other hand the latter, owing to their empirical character, were opposed to fruitful scientific logic, which is not content with facts and figures given without explanation or connection. They could not completely satisfy practical men, who felt that they were

groping blindly, and who quite realised that the sample to be tested, in consequence of unforeseeable heterogeneities, might not even show the mean resistance of the piece from which it was taken.

Thus there was a notable dearth of scientific methods of examination with regard to the brittleness of metals; and this became more evident and more serious when, as metallurgy progressed, the attempt was made rationally to perfect thermic processes, such as annealing, tempering and the like.

It is obviously impossible to make sure of obtaining better results from a given process, if the essential character of the phenomena upon which it depends is not properly understood. Now chemistry and mechanics could give no clue to these phenomena, but could only record the consequences, such as the different chemical properties of carbon in annealed and tempered steel, and the variation in the amount of resistance.

Both science and technology felt the want of a more searching and thorough investigation into metals, in order to understand, not their raw centesimal composition, but their internal structure, their crystalline morphology, the condition in which chemical elements are met with within them, and, so to speak, the histological distribution of the latter.

Means were devised of literally looking inside metals, either with the naked eye or by the aid of magnifiers. The first discovery, that of Widman-

stätten, is due to them ; he made it during the oxida-
tion by heat of smooth samples of certain kinds of
meteoric iron and while observing the action of acids
upon them.

This occurrence brought about, from the outset, a
relationship between metallography and petrography,
which became even closer when Sorby gave the new
science its first really vital impulse.

In 1857 and 1858, whilst he was publishing his
observations upon thin sections of rock, he noticed
that metals bore very striking analogies to it ; and,
after dealing with transparent specimens, he passed
on to those of opaque bodies, especially of wrought
and cast iron and of steel.

In 1864 he published a memorandum on the
subject.

In 1878 Martens took it up, dealing particularly
with crystallisation, breakages and defects of fusion.
Metallography became practical owing to him and to
his assiduous labours, never interrupted to this day.
Sorby, too, in papers published in 1882, 1886 and
1887, dealt with the same topic.

During this period a gigantic stride was taken by
Osmond and Werth in " The Cellular Structure of
Iron and Steel," entered, in 1883, at the Academy of
Sciences and published, in 1885, in the " Annales des
Mines." In this essay the two scientists laid the
foundations of the allotropic theory with regard to
iron.

Meanwhile Wedding, Stead and Arnold were contributing to this investigation.

From about 1885 metallography remained, for some years, at a standstill, but after 1894 it attained, almost at a bound, to scientific and industrial popularity.

In 1894 Osmond published his memorandum " On the Composition of Charcoal Steel," which became the text-book and limit of modern metallography. This work gives constant, and in practice rather complex, rules for the mechanical manipulations that precede examination under the microscope. These methods were taken up by Le Chatelier, adopted as a whole, and, by means of the daily experience furnished by strenuous laboratory work, simplified as much as possible, and carried to perfection even in the smallest details.

Osmond co-ordinated the pre-existing notions on the correct interpretation of internal structure and on the composition of steel ; but he put forward many greater and newer ideas and opened up vast fields to investigation. He began a gigantic chapter of science, and called others to collaborate in its development and continuation.

To this the best talent of modern science devoted itself. Foremost was Le Chatelier, who worked indefatigably to render metallography practical and its use common.

Both directly and through his pupil Guillet, he

bridged the chasm that had always separated the laboratory and the workshop, and carried the new ideas and the new methods of minute and patient investigation into the centre of the gigantic and noisy metallurgical establishments. It may be said, in short, that the present metallographic system is that invented by Osmond and perfected by Le Chatelier.

All the systems of previous workers, however praiseworthy, now have a merely historical value, and a description of them would be devoid of interest. They present no differences in principle, and are but successive phases of an evolution.

The actual method simply follows forms and a mode of manipulation different from those that preceded them, and they are of such a nature as to produce a remarkable saving of time.

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CHAPTER II.

PREPARATION OF SAMPLES.

Cutting.—When a piece of metal is presented for metallographic examination, it is necessary, first of all, to detach from it a sample of the right size for the successive manipulations and observation.

Since the metallographic microscope leaves preparation quite free, and the piece is simply laid on it as on a platform, with the polished side downwards, facing the object glass, there is the greatest latitude in determining the size of the sample. Le Chatelier, for instance, examined a Falk joint for tram rails, 250 mm. long.

Still, when there are not special requirements, it is considered advisable to choose a sample from 2 to 4 cm. square, and about 2 cm. thick, for burnishing.

The separation from the bar can easily be accomplished, by means of a hand or machine saw, in the case of all metals not harder than annealed steel.

Hard but brittle metals, like white cast-iron, can be broken with a hammer.

Hard metals, difficult to break, like tempered steel that has been slightly softened, are cut by power with

a thin emery or corundum wheel. This system is also preferable to breakage by hammer in the case of hard and brittle metals, as it gives more regular samples.

First Polish.—The separated piece is freed from rough irregularities, and the surface to be prepared for the microscope is rendered as smooth as possible.

This is first done by means of increasingly fine files, and afterwards by rubbing the sample with powdered emery, on cloth-covered blocks. Powder of several decreasing degrees of fineness is required, and this is obtained by levigation in water, for which Le Chatelier's apparatus (Fig. 1) is used. The commercial emery, coming from the top, meets an ascending stream of water, which carries off its lighter parts and deposits them in a vessel. Different degrees of grain in the emery are obtained according to the velocity of the current of water. At present, however, ordinary emery paper, if carefully prepared, is generally considered adequate. First a coarse sheet is employed to remove the marks left by the file, the sample being rubbed at right angles to them. The direction is changed back again while the traces of the coarse paper are obliterated by means of a medium sheet, and while the process is repeated with a finer one. The coarseness of the emery on the papers, and the number of them necessary, varies with the hardness of the sample   The softer this is, the more care it requires, as its surface is more sensitive.

In every case, before passing from one paper to the

FIG. 1.—Le Chatelier's Apparatus for Levigating Emery.

next, the sample and the hands must be well washed
with soap and water, to prevent grains of the coarser
emery from being left to spoil the succeeding polish.

The rubbings with emery are followed by others,
exactly similar, with " potées."   These are impalpable
corundum powders ; they are either already prepared,
or placed in the water on frames covered with cloth.
A judicious selection of them gives the sample the
appearance of a mirror, and leaves only very slight
channellings, hardly visible to the naked eye. Washing
with soap and water is also necessary in the case of
the " potées."

All work with polishing papers is greatly facilitated
by moistening them with a few drops of essence of
turpentine.

Burnishing.—The sample to be microscopically ex-
amined must not show any marks of mechanical treat-
ment, even under the most powerful magnifiers.   It
must therefore be subjected to final preparation by
means of hard substances so fine as to leave no trace
visible through any object-glass.   The extreme sub-
division involved can only be obtained by means of
chemical processes.

Precipitated oxide of iron and of chromium have
been used, but oxide of aluminium is now alone re-
sorted to.   It is prepared by chemically calcinating
pure bisulphate of aluminium and ammonium.

The oxide obtained is in extremely minute parti-
cles, and of great mineralogical hardness.   It would

be impossible to divide them further, but it is necessary to break up the agglomerations of particles formed during calcination. To this end the oxide is put, with distilled water, into a small spherical mill, completely lined with porcelain inside, and is slowly ground for an hour. The sludge from the mill is disseminated in water, in the proportion of 10 grammes of pre cipitate per litre. After 1 per cent. of nitric acid has been added, the mixture is shaken and left to stand for about an hour, in order to obtain the solution of any extraneous salts which, in spite of the care taken, may remain. Then it is washed by decantation with distilled water, until the acid reaction has disappeared. At this stage, the oxide begins to float in the water, a property which is increased by adding 2 c.c. of ammonia per litre, taking care to maintain the same ratio between the volume of the liquid and the weight of the oxide.

The whole is then put into Le Chatelier's special apparatus (Fig. 2). This consists of a long glass tube, whose sides taper at the base, at an angle of about 20°, to an aperture, 3 mm. in diameter. At the top of the tube, which holds a litre, there is a cock, provided with an opening at the side. The ammoniacal liquid is sucked up into the tube from the top, and is kept hanging, as it were, motionless within it. The particles of alumina, beginning with the largest, form a deposit, which can be distinctly seen in the conical lower part : it is removed first, without disturbing

FIG. 2.—Apparatus for Levigating Alumina.

the rest of the liquid, by slightly opening the cock at the top. The alumina deposited within the first quarter of an hour is thrown away, as it is too coarse to be used. The deposit is next removed at the end of an hour, and this alumina is employed for the first burnishing. After 4 hours more a product is obtained sufficient for iron and steel, which, as has been said, are the easiest to prepare. The product of 24 hours' standing is suitable for bronze and brass of ordinary hardness. After this has been removed, the ammonia added to the liquid is saturated with acetic acid, and then all the powder still suspended, which is used for more tender metals, quickly falls.

All these operations must be carried out with the most scrupulous cleanliness, to keep extraneous matter out of the alumina. Atmospheric dust must be avoided, and to this end the different powders are kept in well-closed vessels. When required for burnishing, the alumina is disseminated in distilled water, and put into an ordinary spray-diffuser, which projects it upon the polishing cloth or felt. The cloth is stretched upon discs revolved very rapidly by special pedal or power machines, such as Grauer's and Frémont's (Fig. 3), which give the required velocity.

The discs are screwed to the ends of the axle, so as to present a large smooth and free surface. One disc must be used for each grade of alumina. The cloth must be free from all silicious or other hard substances, while the discs must always be protected from

FIG. 3.—Frémont's Machine.

dust, and only be uncovered during use. The burnishing is done by lightly pressing the specimen against the cloth, and constantly spraying on it the water charged with alumina, so as to prevent heating. It is advisable to constantly change the position of the specimen on the disc, by making it revolve upon its own axis, in order that the action upon it may be uniform.

At this stage the polished surface must not be touched again, either with the hand or with a cloth. It must be washed with water from time to time to remove the alumina, and quickly dried with alcohol to prevent oxidation. Then it is put under the microscope to see if any grooves remain, and the treatment is repeated until none are left.

Such is the method generally adopted; and it is amply sufficient for all metals, save in the exceptional case of extremely soft alloys.

The suggestion has been made that a mirror-like surface could be obtained by casting on a mica plate (Hannover), or on one of glass or polished steel (Ewing and Rosenheim), but this caused a sudden cooling, capable of affecting the internal structure of the metal. Le Chatelier proposed to place a sheet of glass within the molten metal, and allow the whole to cool together.

Action.—The polished side presents under the microscope nothing but a smooth mirror-like surface, broken only by the cavities left by non-metallic substances removed during the cleansing process, such as slag or graphite.

A satisfactory examination demands the differentiation of the various components of the product dealt with ; advantage being taken of their several properties to develop the picture of the internal composition, as it were, on the polished surface.

Mechanical Action.—This is based on the different degrees of hardness of the components of a complex substance, and, therefore, on the difference in wear produced by friction. The rubbing surface employed must be sufficiently elastic to adapt itself to the inequalities that are formed and to enter into the smallest fissures. Parchment, damped and stretched over a block of hard wood, is employed, and water, with precipitated sulphate of lime, is thrown upon it. (Osmond.)

Mixed Action.—This is obtained by the addition to the rubbing substance of another that does not react chemically upon the surface except during friction. Such is the 3 per cent. solution of ammonium-nitrate. Osmond also employed an infusion of liquorice root, which produced the same effect. Indeed, it contains glycyrrhizine, the ammoniated salt of an azotated glucoside having an acid reaction, which is doubled, probably owing to a soluble ferment.

Chemical Action.—This is the most often used. It must be capable of being gauged to a nicety, in order not to corrode the metal too deeply, and must proceed very slowly. Diluted reagents are employed, and are allowed to fall, drop by drop, upon the surface, until they cover it. The process is followed with the

eye, and is interrupted at the desired moment by a jet of water. Washing with alcohol and dessication by means of a blast of well-dried air follow.

When the action requires much time, the sample is placed face downwards in a watch-glass or a capsule containing the reagent.

The substances employed are very numerous, and vary according to the metal treated and to the component which it is proposed to seek out and bring into prominence.

Each case will be dealt with separately, in connection with the component thus singled out.

Electrolytic Action.—This is accomplished by means of an electric current passing through a liquid that does not itself act upon the metal.

The reagent is placed in a platinum capsule, in which the specimen is laid upon a piece of filtering paper. The negative pole is connected with the capsule, the positive one with the specimen, and a current of from 4 to 5 volts, whose intensity can easily be varied from a thousandth to a hundredth of an ampère per square centimètre, is switched on. In this way every grade of action can be obtained, and it can be increased at will by modifying the intensity of the current and the duration of the action. The liquid naturally varies with the metal. Diluted solutions of potash or ammonia are used for copper alloys, and a cold, neutral solution of persulphate of potash, or a warm, neutral one of hyposulphite of soda, for iron.

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This system is a return to the method proposed by Charpy for acting upon brass, which consists of laying it on a platinum slab substituted for the zinc. If the zinc in the brass is less than 50 per cent., an ordinary Daniell's battery is used, if more, a Lalande battery.

Action by Oxidation.—Stead proposed this, and called it the " constitutional " method. It consists in heating the proposed specimen in air. Partial and localised oxidations are produced on the sample, and often suffice to point out the composition of the metal.

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CHAPTER III.

THE MICROSCOPE

THE sample having been burnished and acted upon, it is necessary to illuminate it in order to examine it with the microscope. As it is opaque, the illuminating pencil of light can only reach it from the side of the object glass, and through it. This has led to the construction of special microscopes for metallography.

The Cornu-Charpy microscope was one of ordinary form, into which light was introduced by means of a lateral tube, a mirror and four little plates of glass placed one above the other, at 45° before the object-glass. The pencil reflected upon these plates traversed the object-glass, was reflected upon the sample, and, passing back through the plates, reached the eye-piece.

The Nachet microscope was also exactly like the common forms, and illuminated by means of the Guillemin-Nachet prism, placed before the object-glass.

These microscopes made it necessary to burnish the sample on both sides, and to grind them exactly parallel, so that the surfaces might be placed at right angles to the axis of the instrument. Moreover, the vertical position of the body was highly inconvenient for photography, when the camera was to be substituted for the eye-piece.

As it would involve too great a digression from the field of metallography proper to enter more fully into the successive evolution of these microscopes, it is advisable at once to describe Le Chatelier's more modern instrument, shown in Figs. 4 and 5.

The object-glass D, is inverted and turned upwards in order that one side alone of the sample need be prepared, and that no limits need be imposed as to its size. The sample is supported over the object-glass by a rigid perforated stand. The stand consists of a stage fitted with three milled screws, by means of which the sample can be moved right or left, up or down, or rotated in one plane.

It is thus possible successively to examine or photograph several points on the same sample, without moving it on the stage.

The focussing is effected by a vertical movement of the stage, and by a rack and pinion, with a fine adjustment, so arranged as to be worked from a distance, when photographing, by a flexible arbor.

In order to illuminate the metallic surface through the object-glass, the image from a luminous source N, is projected through a lens on the diaphragm M. The pencil of light passes through the collimator L, a second diaphragm K, and by means of a prism I, properly cut, and constituting the essential element of the system, rises through the object-glass and is reflected on the prepared surfaces. Thence it returns through the object-glass, and reaches the eye-piece
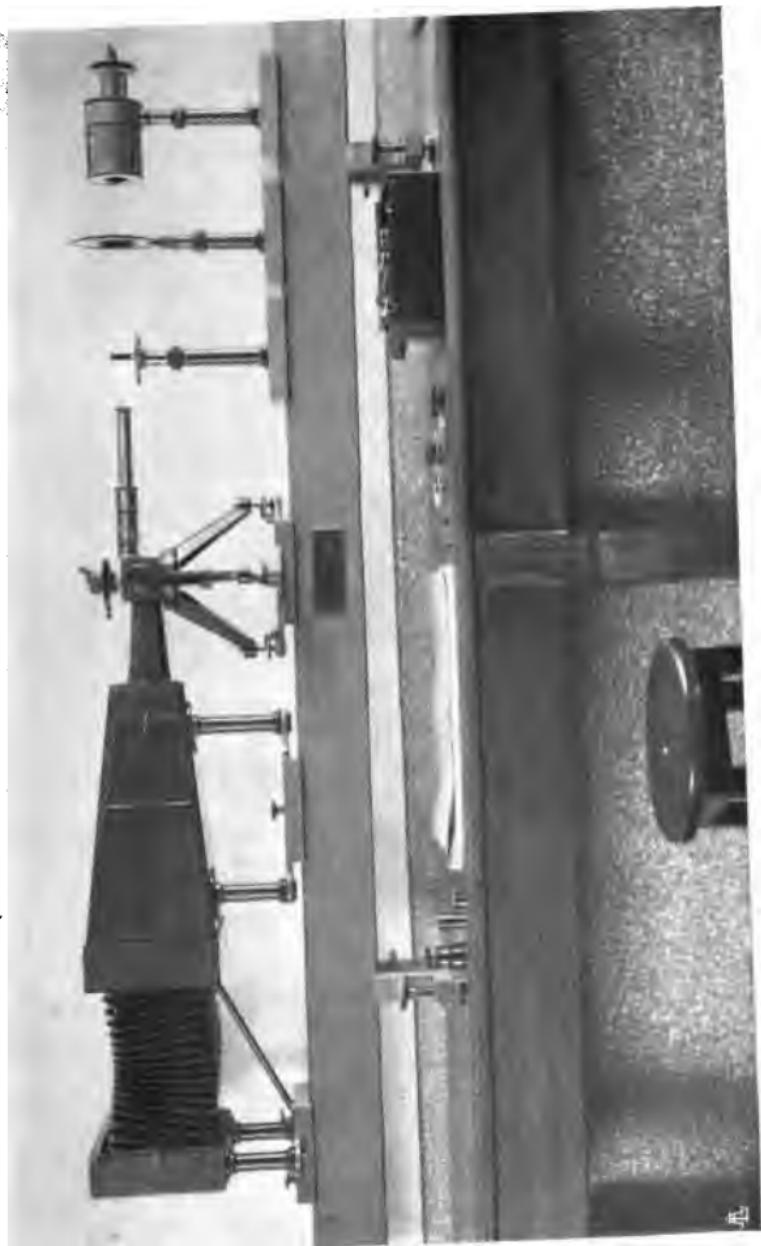
Fig. 4.—Le Chatelier's Microscope.

through the totally reflecting prism E.   This, as may
be seen, is mounted on a horizontal axis, and therefore
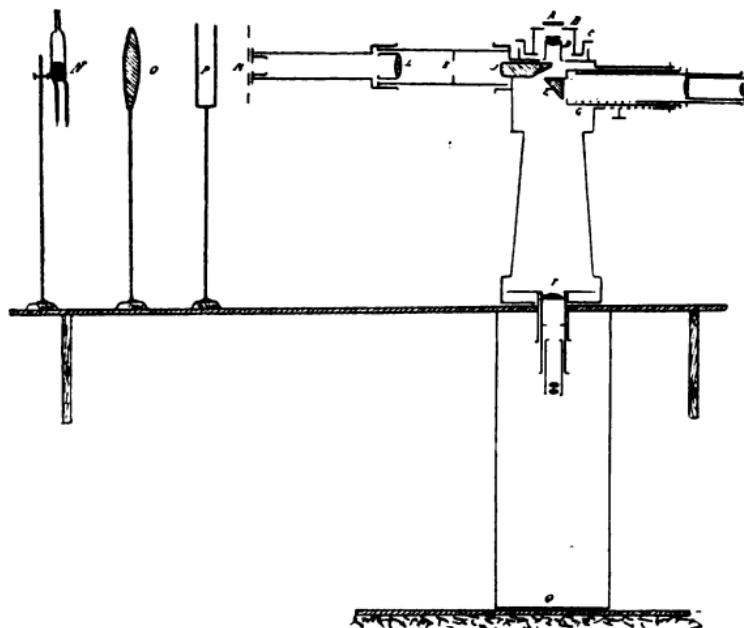
FIG. 5.—Section of complete Micrographic Apparatus, with
Le Chatelier's Instrument.

allows the investigator to sit while working.   The prism
E can be turned through 90° on a vertical axis,* thus
throwing the image, not into the eye-piece, but at right
angles to it.   The camera is placed in the latter

* In Fig. 5, for the sake of clearness, the camera has a
vertical axis, as in the original form of this microscope.   The
prism therefore revolves on a horizontal axis.
    The letterpress, on the other hand, refers to the form shown
in Fig. 4, in which the camera has a horizontal axis.

direction. A projection eye-piece, magnifying about two diameters, is usually fitted in front of the camera.

The microscope can give almost any degree of enlargement, as both the object-glass and the eye-piece can be changed at will.

The Nernst electric lamp is now universally used as a source of illumination, the naked light being adopted for photography and ground glass for direct vision.

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CHAPTER IV.

METALLOGRAPHIC EXAMINATION.

BOTH metals taken singly, and alloys formed by the mixture of metals alone or of these and other substances, are capable of metallographic examination.

Pure Metals.—These present to the microscope a network of hexagonal polygons, which reveals a polyhedric structure. The sides of the polygons represent the surface of separation between one polyhedron and another. The hexagonal structure confirms the cubic system of crystallisation in metals, since these polyhedra probably constitute the resultant of the interposition of cubes with octahedra. Moreover, these grains, deeply acted upon by the proper reagents, and examined under a strong glass, appear constituted by a collection of little cubic crystals, all equally orientated in the same grain, and in a manner differing with each grain. This fact, which occasions different refractions of light, explains the variety of tints which the grains of the same metal present to the microscope (Fig. 6).

The size of the grains differs considerably, and depends upon the greater or less purity of the metal, and

upon the vicissitudes of temperature through which it has passed.

A very slight mixture of chromium, for instance, contracts the grain of the iron in a remarkable degree.
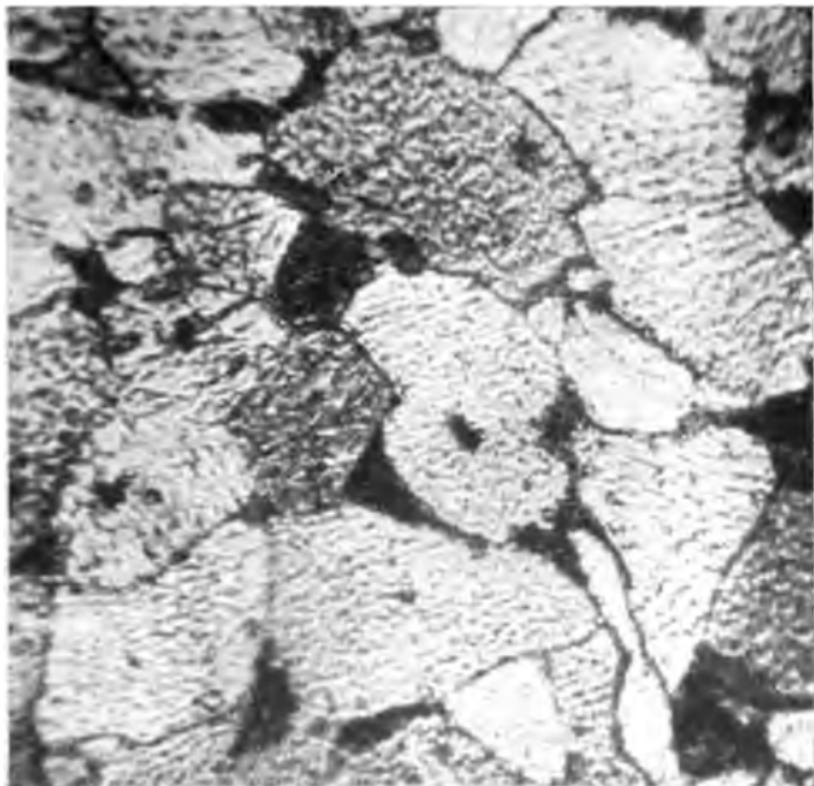
FIG. 6.—Almost Pure Iron (Extra Soft Steel).
Magnified 650 diameters.

Thus, as a rule—conformably, indeed, to the general laws of crystallisation—a metal has larger

grains in proportion as it has been cooled more slowly and from a higher initial temperature.

Mechanical elaboration has great influence upon internal composition. If wrought cold, the grains are compressed and lengthened out in the direction of the working; if wrought hot, and while the metal is cooling, crystallisation is obstructed, and the resulting structure is very close, while it is amorphous at the edges.

The dimensions of the grain, as we shall see, are always strictly related to the physical properties of the metal, which is tough and malleable in proportion as the grains are small. Hence the micrographic examination of a pure, or practically pure, metal, essentially composed of only one metallic element, reveals its thermic and mechanical vicissitudes, by showing the dimensions of the crystals composing it and the degree of their deformation. Besides, the microscope makes known the greater or lesser degree of purity, passing judgment on the quantity of heterogeneous substances lying between the characteristic polyhedra, and capable of lessening the resistance of the metal.

This is true, for instance, of the slag contained in puddled iron, in which it breaks the continuity, as it has very little cohesion with the grains with which it comes in contact.

In this case a third criterion is added to the two already mentioned, and from the sum of the examinations a sufficiently complete conception may be obtained of the physical properties of the metal.

An idea of the composition of a nearly pure metal is given by Figs. 6 and 7, almost entirely occupied by iron crystals, with rare interpositions of other substances, which appear black in the picture.   In one of the two (Fig. 7) the crystals are deformed by cold elaboration.

Alloys.—For the most part the metallic substances met with contain, as components, several chemical elements and are actually comprised under the generic name of alloys, even when a metalloid enters into their composition.

Several phenomena may take place when the components of an alloy come together.   If there be two components the four chief possible results are as follows :—

    I. The resolving of one component into the other.

   II. A chemical combination, and the formation of a composite having definite proportions.

  III. A mechanical mixture.

  IV. The formation of a composite having definite proportions, and subsequently resolving itself into one of the components.

These different phenomena generally accompany each pair of components, either simultaneously or in succession.

Hence metallic alloys are not homogeneous bodies, but agglomerations of various components, which, in
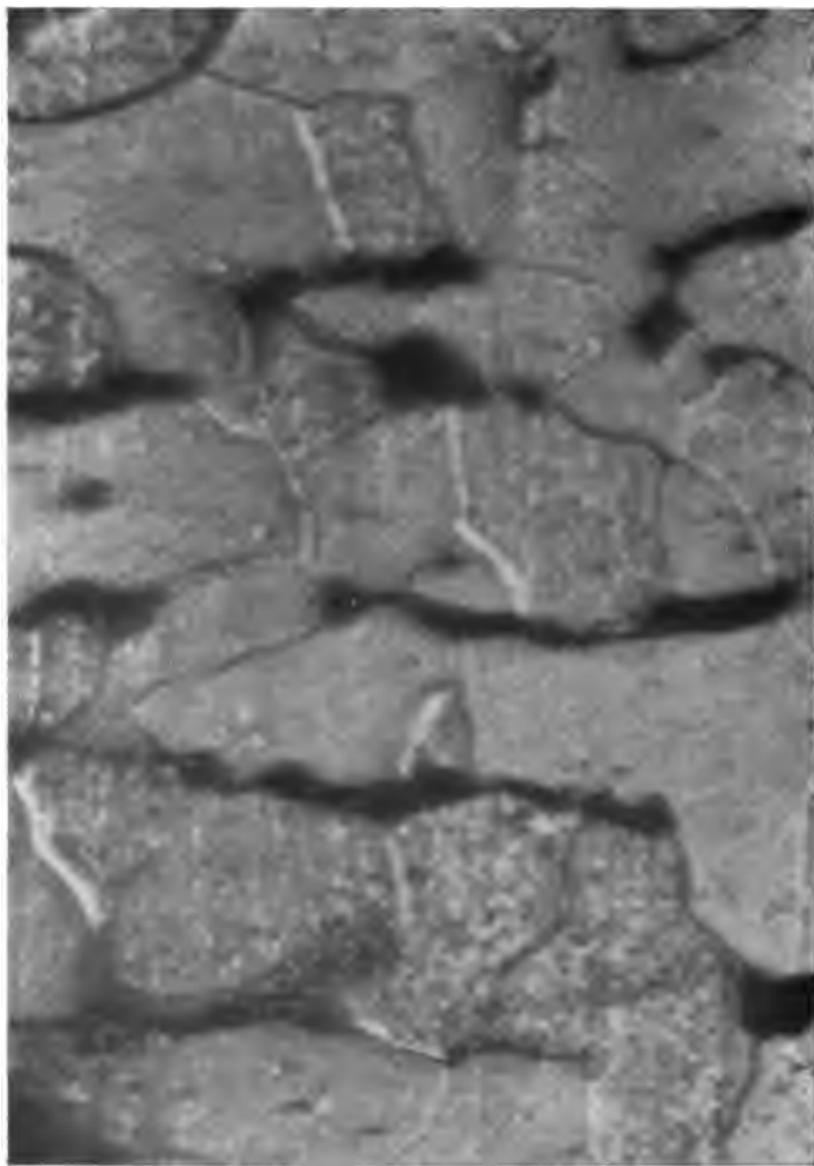
FIG. 7.—Cold-wrought Iron.   Magnified 1100 diameters.

their turn, are either definite chemical composites, or solutions, or mixtures.

There is a complete analogy between alloys and rocks. As the latter are formed by the union of several minerals, the former are caused by the union of the various components spoken of.

The appearance, disappearance and predominance of each of them depends upon the variation in the quantitative ratio between the components, on the variations in their physical condition and on the order in which the latter have taken place.

These general principles are amply illustrated by experiment. Metallographic examination, which enables all these phenomena to be traced in alloys, can therefore furnish full information as to the chemical composition and the physical vicissitudes of the sample.

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CHAPTER V.

IRON AND ITS ALLOYS.

IT will be necessary to preface this most important chapter of metallography by a few notes on the theories now adopted to explain the multiple phenomena presented by iron and its alloys, such as steel, cast-iron, special steel and special alloys.

It is now admitted that iron can assume three chief allotropic states, transforming itself successively from the one into the other, according to its physical and chemical condition.

This theory, which, in consequence of the researches of Osmond, Le Chatelier, and Roberts-Austen, may now be called a fact, owes its origin to the anomalies of heating and cooling observed in iron and its alloys.

Behaviour of Pure Iron.—If a piece of pure iron is heated, a slower rise of temperature is noticed at 740°,* and a much more marked one at 860°. There is thus a special absorption of heat.

In cooling there are different phenomena. Almost at the same temperatures, save for slight differences due to a phenomenon connected with hysteresis, there

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* The degrees of Temperature throughout are *Centigrade.*

are emissions of heat, with consequent delay in the lowering of the temperature, and even, sometimes, with a rise.

At these points the physical and chemical properties of iron undergo abrupt changes. Iron, at $740°$, is said to be in the allotropic state a. Such iron crystallises into the cubic system, is not hard, is fairly firm and malleable, and is magnetic. It is generally considered incapable of dissolving carbon, but recent investigation points to its possessing some solvent power, though slight.

Between $740°$ and $860°$ iron is said to be in β condition. It is cubic, hard, not magnetic, and incapable of dissolving carbon. Beyond $860°$ iron is said to be in the γ state. It is soft, not magnetic, and has a very strong solvent power with respect to carbon.

Electric resistance, increasing by tens from $0°$ to $860°$, remains constant in γ iron. This, according to Osmond, crystallises into the monometric system, and, according to Le Chatelier, into rhombohedra very similar to cubes.

These points of allotropic transformation are termed thermal change-points.

In the case of pure iron, the neighbourhood of $740°$ is called Ac_2 for heat and Ar_2 for cooling, and that of $860°$ Ac_3 and Ar_3 respectively.

The temperatures Ac_2 and Ac_3 are always greater, in the same sample, than the corresponding Ar_2 and Ar_3, and this difference sometimes amounts to several

tens of degrees; it is due, as has been said, to a phenomenon connected with hysteresis. Roberts-Austen speaks of another change-point at 600°, and Ball and Curie of one at 1300°, but the existence of the latter is controverted.

Behaviour of Iron Alloys. Iron and Carbon.— When iron contains carbon, it has a third change-point, in the neighbourhood of 680°, called A_1, whereas, as has been seen, the change-points of α iron into β iron and of β iron into γ iron are respectively called A_2 and A_8.

During the heating of a ferro-carbon alloy there is a strong absorption of heat at 680°; on cooling there is a quick emission, visible to the naked eye, as the light irradiated by the iron suddenly revives. This point is therefore called the re-heating point.

There are similar anomalies in the course of expansion.

The change-point A_8, which is at 860° for pure iron, falls rapidly, when this contains carbon, with the increase of the latter, whereas the point A_2 remains constant up to 0·35 per cent. of carbon.

Here A_8 and A_2 blend, so as to form one single point, A_8A_2, which begins to fall in its turn, until, with 0·83 per cent. of carbon, it blends with A_1.

This third change-point remains constant in the neighbourhood of 680°.

These phenomena are universally interpreted as follows :—

The ferro-carbon alloy, under ordinary conditions, i.e. as it can be obtained by fusion, and at temperatures below 680°, contains carbon (up to 6·6 per cent.) in the form of carbide of iron Fe_3C.

At 680° this carbide separates into iron and carbon, and the absorption of heat required for the separation explains the slower rise in temperature.

Reciprocally, when the ferro-carbon alloy cools, beginning at temperatures above 680°, the carbide Fe_3C reforms, and the heat of the formation of this composite explains the sudden rise in temperature.

The changes experienced by the other two change-points remain to be explained. For this purpose Osmond's comparison may be used.

We know that carbon is insoluble, or nearly so, in a and β iron, and is, on the contrary, highly soluble in γ iron.

As common salt, dissolved in water, causes the latter to form at temperatures below freezing-point, liquefying ice below its fusion point, so free carbon anticipates the formation of γ iron, in the quantity necessary to dissolve it, and the phenomenon, i.e. the lowering of the change-point A_3, is the more marked in proportion to the amount of carbon set free, or, in other words, of carbide dissolved.

A β iron, on the other hand, does not dissolve carbon, its point of formation A_2, remains invariable at 640°, and A_3, falling, attains to it.

As the quantity of carbon increases, γ iron is pro-

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duced at an ever lower temperature and in ever greater quantity, until, at 0·35 per cent. of carbon, the production of β iron is entirely eliminated, and γ iron, at 740°, is converted straightway into α iron.

Not all, however, for part remains to keep the carbon in solution—naturally more concentrated— and does so up to 680°, at which temperature carbide can reform, and the carbon sets its solvent free.
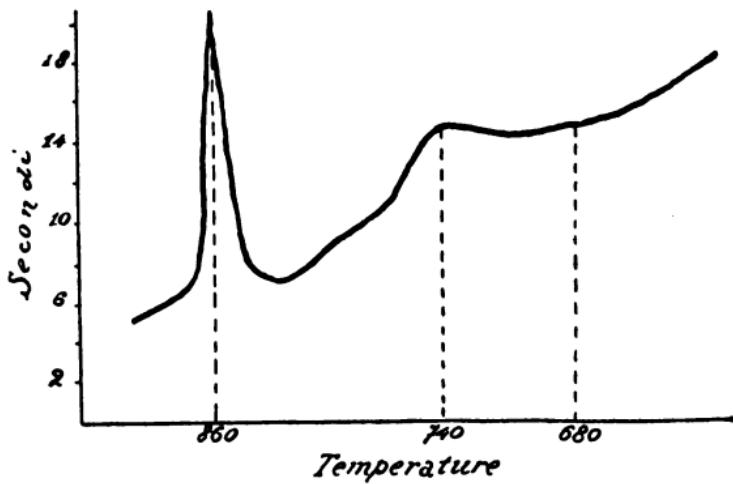
FIG. 8.

Here, too, the quantity of iron maintained in the γ state increases with the percentage of carbon, and, for 0·85 per cent. the whole of the iron remains in the γ state up to 680°.

The phenomena hitherto mentioned suffice to explain the chief results of metallography.

They are illustrated by the accompanying diagrams. Osmond's diagram (Fig. 8) represents the curve of the cooling of pure iron (as far as it can practically be such), with its change-points.
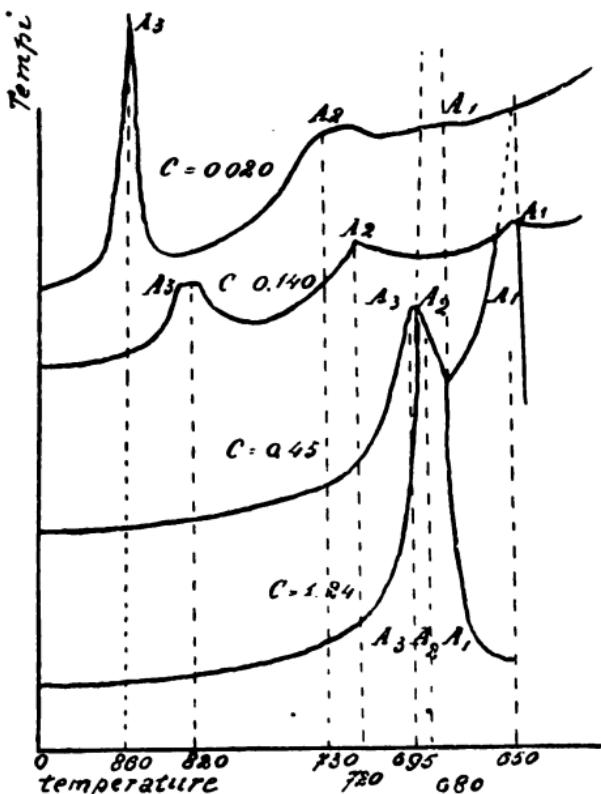
FIG. 9.

The abscissæ represent the temperatures, the ordinates represent quantities inversely proportional to the speed of cooling, and, more precisely, the time,

in seconds, which the needle of the galvanometer of the electro-thermometer measuring the temperatures occupies in passing over a given interval.

The curve rises to a point at 860°, a swelling at 740°, and a slighter one at 680°, due to a very small quantity of carbon.

The second diagram (Fig. 9), also Osmond's, refers to different kinds of steel, for increasing percentages of carbon.

The last diagram (Fig. 10), is part of that of
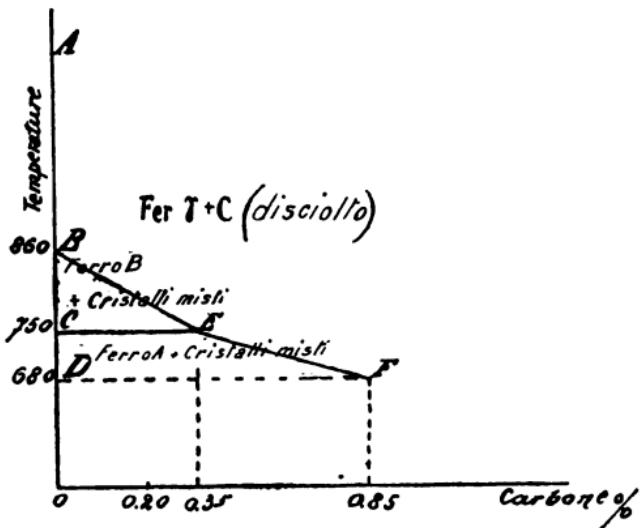
FIG. 10.

Bakkhuis-Roozeboom on the equilibrium of ferro-carbon alloys, and describes the preceding phenomena ; representing the composition of the alloy, for every

pair of values of the two variable factors, viz. per-
centage of carbon and of temperature.

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CHAPTER VI.

COMPONENTS OF FERRO-CARBON ALLOYS.

ACCORDING to the comparison already instituted between alloys and rocks, the components of the former correspond with the different minerals which form the latter.

Ferrite.—This is composed of pure α iron, or of α iron joined to such bodies as are capable of forming with it isomorphous mixtures or solid solutions, such as silicium, nickel, manganese, etc. It exists in iron and in steel with less than 0·85 per cent. of carbon, and only exceptionally in very silicious grey cast-iron. It appears in polyhedric grains, composed of small cubes differently orientated from grain to grain and, therefore, differently coloured (Fig. 11).

It is brought into view by the action of tincture of iodine, with a 5 per cent. solution of picric acid in absolute alcohol, but especially with an 8 per cent. watery solution of ammoniacal chloride of copper.

Action with a 4 per cent. solution of nitric acid in amylic acid shows the outline of the granules very

clearly, and is applied with great safety to gauge brittle steel, in which these outlines are extraordinarily neat and well defined (Fig. 37).
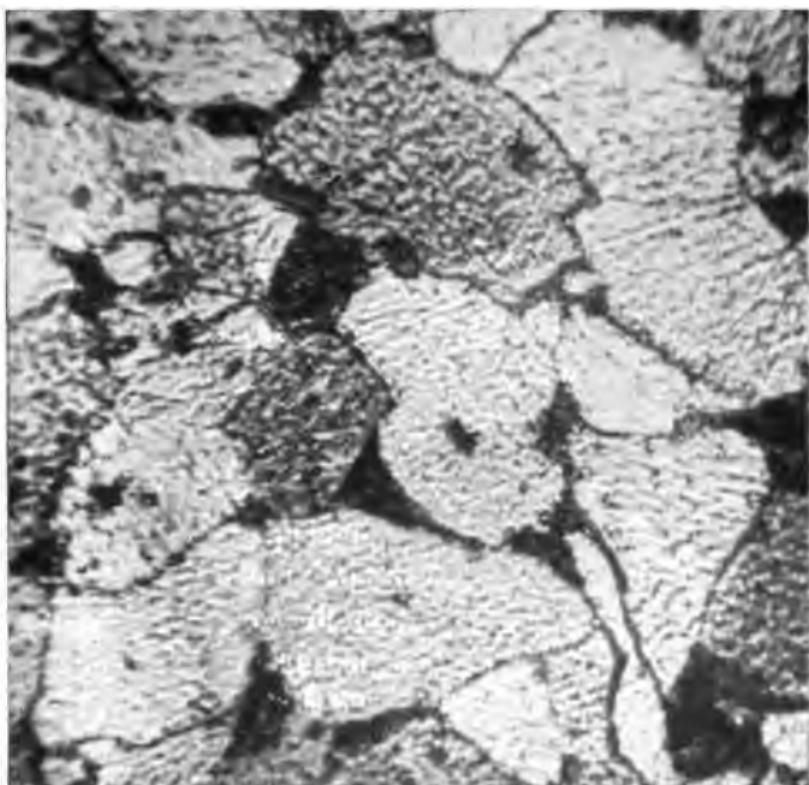
FIG. 11.—Almost Pure Iron (Extra Soft Steel).
Magnified 650 diameters.

Ferrite is very soft, and can be scratched with a needle. The presence of silicium greatly increases the size of the grains and the proper formation of the

crystals ; the presence of chromium, on the contrary, lessens their dimensions considerably.

Bénédicks' recent investigations on steel have shown, in a manner to be described later, that when the alloy contains more than 0·5 per cent. of carbon, this is dissolved, even by ferrite, though only in small quantities (0·27 per cent.). This is contrary to the general idea that a iron has absolutely no solvent power over carbon.

Bénédicks proposed to call ferrite, when it contains 0·27 per cent. of carbon, ferronite, but perhaps this name may not be necessary, since several isomorphous solutions and mixtures are comprised under the term ferrite.

Cementite.—This is carbide of iron Fe_3C, containing 6·67 per cent. of carbon. It is very hard (its hardness is 6·5). It is soluble in sulphuric acid, in nitric acid, and in concentrated boiling hydrochloric acid. It is not acted upon by cold dilute hydrochloric acid, and it can thus be separated and gathered under the form of little black straws. Cementite is not coloured by any of the ordinary reagents used for action, and remains white (Fig. 12). It is the same when the sample is boiled for from 10 to 15 minutes in a 25 per cent. solution of caustic soda, with 5 per cent. of picric acid.

Its hardness is also shown by mechanical action, which wears away the other softer components.

Cementite enters with ferrite, as we shall see,

into a euthectic compound, but is not found alone except in highly carburetted products, white cast-

FIG. 12.—Cementite (the light part), in a steel soldered under the oxyacetylenic blowpipe. Magnified 650 diameters. Acted upon by 4 per cent. nitric acid in amylic acid.

iron and hard steel containing over 0·85 per cent. of carbon.

It blends isomorphically with carbide of man--

ganese, Mn_3C, and for small percentages of Mn it is still called cementite.

Cementite, it will be seen, is eliminated at 680°
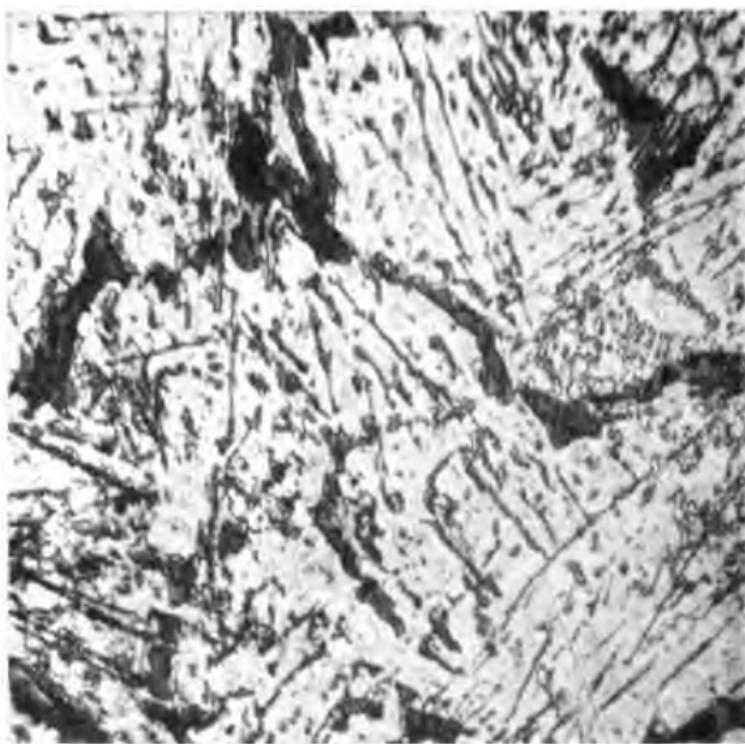
F IG. 13.—Cementite (the black part).   Magnified 650 diameters. The same steel as in Fig. 12.   Acted upon by picrate of soda.

and amalgamates on cooling.   It is also generated by moderate heating of the components which contain it in solution.

Pearlite.—This is a euthectic mixture, similar to the cryohydrates, and is composed, like all euthectics, of alternate layers of two different substances. Pearlite is composed of alternate layers of ferrite and cementite, rarely thicker than one-thousandth of a millimetre.

It appears in black and white sheaves (Fig. 14). The blackness is not caused by real discolouration of one of the components, but by the fact that the softer, i.e. the ferrite, corrodes and becomes concave, more than the other, thus remaining dark.

It generally possesses a mother-of-pearl-like iridescence, due to the alternation of these very thin layers, and to this it owes its name of pearlite.

It is coloured by tincture of iodine, by nitric and picric acids, by mechanical and mixed action.

Pearlite is found in cast iron, in crude and annealed steel (Fig. 15). It contains about 0·85 per cent. of carbon, and the so-called euthectic steel, of which mention will be made, is entirely composed of it.

Pearlite disappears when it is heated above 680°, in consequence of the separation of the cementite. It is reconstituted on cooling, at a temperature but slightly lower.

Sorbite.—This is a component that appears in ferro-carbon alloys, and particularly in steel, when they are quickly cooled through the first change-point (680°), without, however, being tempered, i.e. having heat vigorously subtracted by special agents.

Sorbite may be defined as " pearlite in which the two

components cannot be distinguished, even with the most powerful magnifiers."

The swiftness of cooling, indeed, does not give the
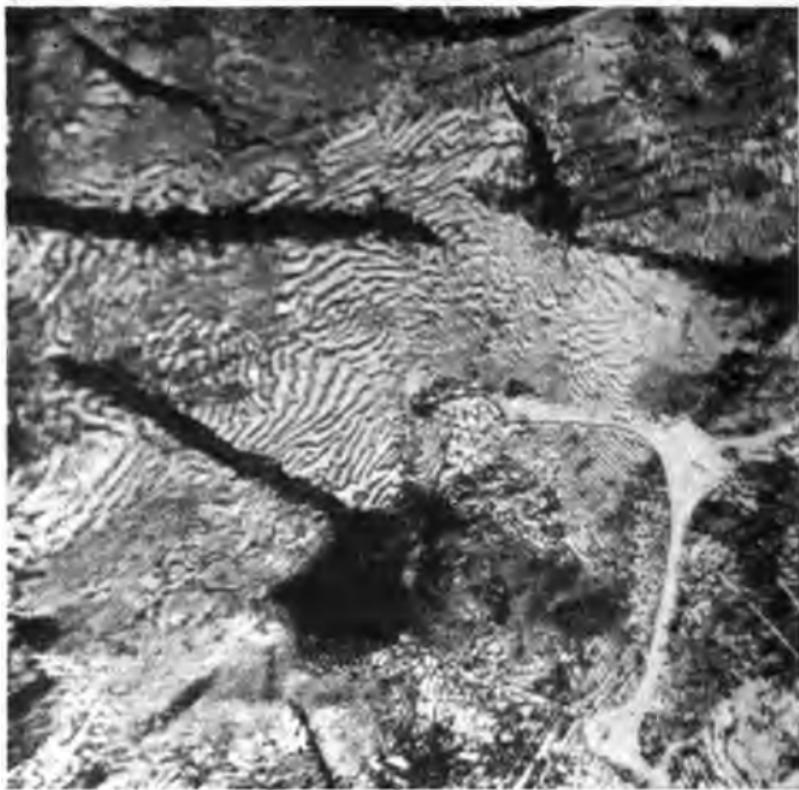
FIG. 14.—Pearlite and Graphite in grey cast-iron. Magnified 650 diameters. Acted upon by picric acid (5 per cent. in ethylic alcohol).

cementite and ferrite time to separate into layers of appreciable thickness. It is, however, believed that

the mean composition of sorbite is the same as that of pearlite.   The latter is also produced when tempered
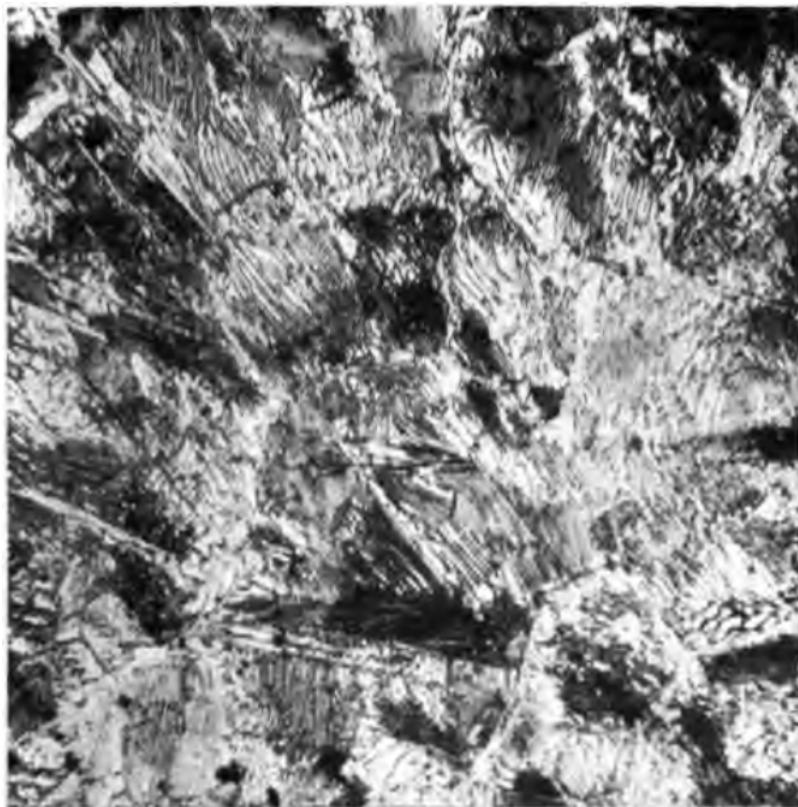
Fig. 15.—Pearlite in very hard steel.   Magnified 650 diameters. Action of 4 per cent. nitric acid in amylic alcohol.   Kourbatoff's reagent.

steel is heated between 200° and 300°, and it is frequently met with in the so-called euthectic steel with

0·85 per cent. of carbon, which is entirely formed by pearlite (Fig. 16).

FIG. 16.—Pearlite and Sorbite (dark spots) in steel at 0·85 per cent. Magnified 650 diameters. Acted upon by 5 per cent. picric acid.

Sorbite is very hard and difficult to break. Hence its formation is encouraged in metal for steel rails and the like.

Such steel, called sorbitic, is obtained by heating above 680°, and then quickly cooling in the air.

Sorbite receives very marked colouring from a 5 per cent. solution of picric acid in absolute alcohol.

Troostite.—This component is formed in steel tempered near the first critical point (680°), or tempered at higher temperatures, but with mild baths, such as oil.

Troostite is seen in black spots (Fig. 17).

Kourbatoff considers it to be a solution of carbon in α iron. It is coloured with a 5 per cent. solution of picric acid in absolute alcohol, and with a 4 per cent. solution of nitric acid in amylic alcohol. It is also coloured with great clearness, and to the exclusion of all other components save troosto-sorbite, by a solution made up of—

> 1 part amylic alcohol
> 1 part ethylic alcohol
> 1 part methylic alcohol

in 4 per cent. solution of nitric acid in acetic anhydride.

(Kourbatoff.)

Martensite.—This is a characteristic component of steel tempered under ordinary conditions, i.e. at a heat slightly over 680° and with a water-bath.

Martensite is very hard and looks like a mass of needles lying in three different directions, that form angles of 60° with one another.

Some observers consider the numberless resulting
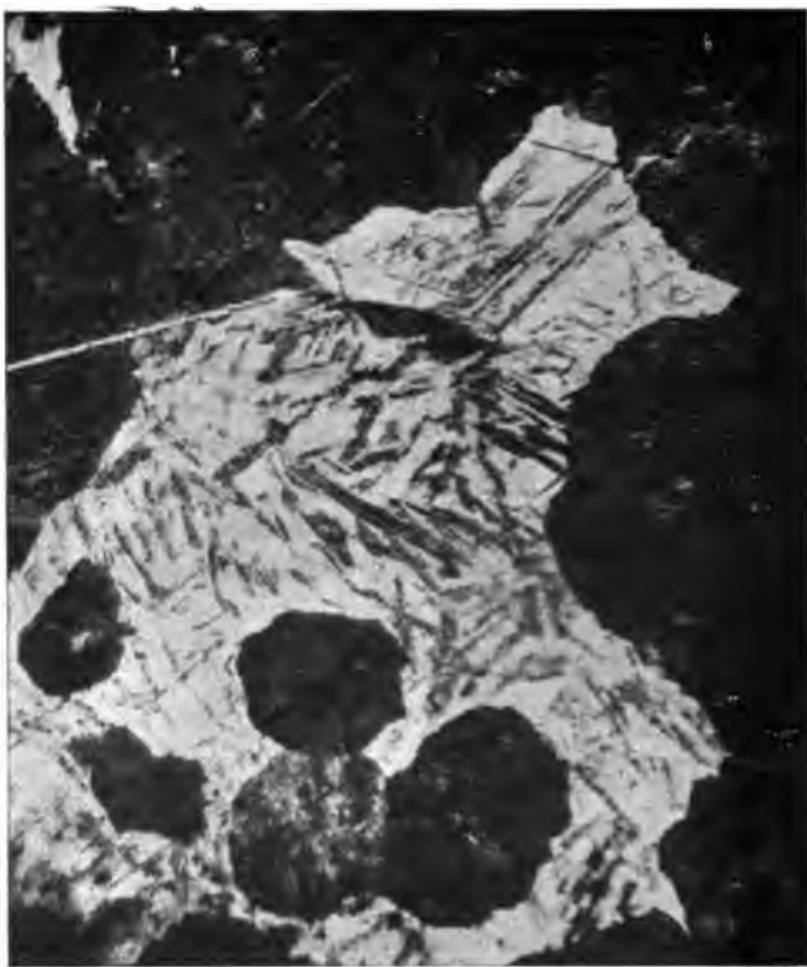
Fig. 17.—Partly tempered Steel. Magnified 650 diameters. Sorbite, dark portion ; Troostite, darker spots in white portion ; Martensite, white portion.   Acted upon by Kourbatoff's reagent (4 per cent. nitric acid).

triangles to be sections of the vertices of the cubes to which they attribute the formation of martensite.
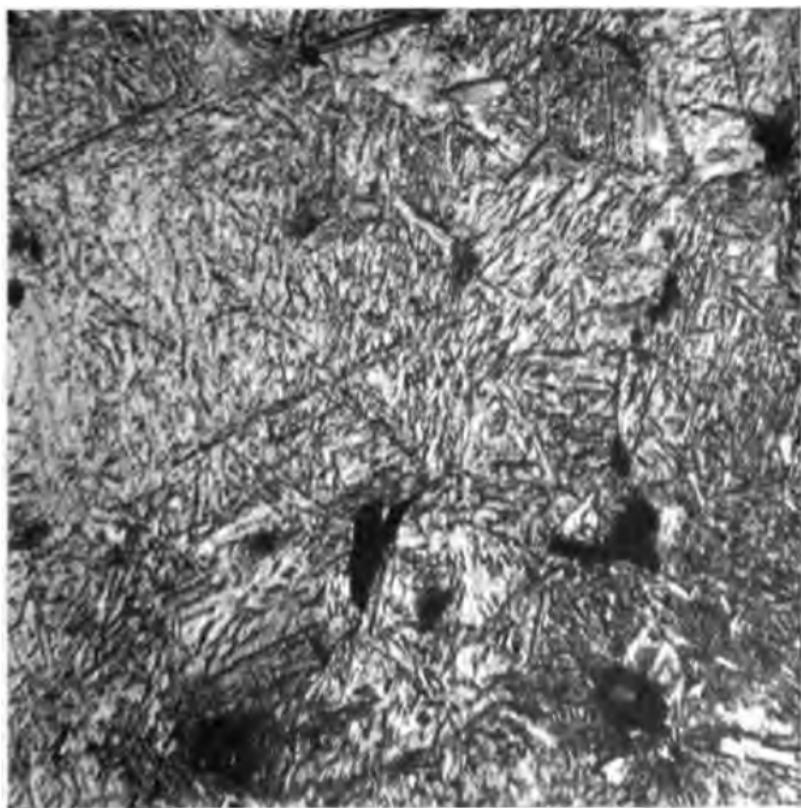
FIG. 18.—Martensite in tempered Steel.   Action by Kourbatoff's reagent.

These needles are only seen under powerful magnification and after strong chemical action.

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They are not coloured by tincture of iodine, but receive a slight colour when the action of picric acid has lasted over 5 minutes.

The composition of martensite varies. Steel with different percentages of carbon, when tempered, is found equally formed of martensite, with identical morphological characteristics.

It was thought that it represented the whole structure of steel, as formed above the change points, kept unaltered by the sudden cooling. But the great hardness of martensite excludes the presence of γ iron, which is very soft; besides, as martensite has distinct magnetic properties, it is necessary to admit the presence in it of α iron, the only phase possessing them. Since hardness, moreover, is peculiar to β iron, a theory has arisen that martensite is an isomorphous mixture of α and β iron.

Heated martensite begins its transformation at $200°$, and first eliminates layers of cementite, round which crystals of sorbite form.

This has given rise to the hypothesis that martensite is a solution of cementite, of varying percentage, in the isomorphous mixture of α and β iron just mentioned.

For these reasons martensite cannot be identified with high temperature steel, but it may be admitted that the latter, under A_3, differs very little from it.

It is from martensite that pearlite is formed, when, at $680°$, the layers of cementite are eliminated.

The crystallographic forms of martensite are the same as those of γ iron, but they are due to a pseudomorphic phenomenon, as will be seen in connection with austenite.

Austenite.—This is obtained when, as Guillet puts it, all the conditions are exaggerated that increase the effect of tempering. For this purpose steel containing 1·1 per cent. of carbon must be taken, heated above 1000°, and subjected to a bath below freezing-point.

Austenite is very soft, so much so that it can easily be scratched with a needle. It is coloured by tincture of iodine. The 10 per cent. solution of picric acid which colours martensite leaves austenite untinted.

Mixed action produces a similar separation.

Metallographers are agreed that austenite is merely γ iron having carbon in solution. It tends particularly to conversion into martensite, and the latter is therefore almost always found with it. This furnishes an explanation for the pseudomorphic form of martensite. The transformation is merely due to the change from γ iron to α and β iron. This explains why it is necessary to temper under conditions dissimilar from those of transformation in order to keep at least part of the iron in the γ state and thus obtain austenite.

Slight warming transforms austenite into martensite, and then into sorbite. At 150° it disappears completely.

Troosto-Sorbite.—This was found by Kourbatoff.

It is obtained with martensite and austenite, by tempering steel very rich in carbon at a high temperature.

It is coloured by the same reagents as troostite, which it resembles greatly, differing only in the manner of its formation. While troostite is found in the midst of pearlite, troosto-sorbite forms irregular black-edged masses, less dark towards the centre, where they generally show cementite.

It would be possible to admit a strong resemblance, if not absolute chemical identity, between troostite and troosto-sorbite, if the widely diffused hypothesis were accepted that troosto-sorbite is generated at a high temperature in a solution of carbon in γ iron, which becomes α iron when cooling.

Troostite, as has been said, is considered to be a solution of carbon in α iron, formed directly at the re-heating temperature. This would give two similar products, obtained under different conditions that explain their structural dissimilarity.

Osmondite.—Heyn discovered this, which is classed as an intermediary between troostite and sorbite. It is considered to be another solution of carbon in α iron, under special physical conditions (hammer-hardened).

Hardenite.—This name has been given to martensite containing 0·85 per cent. of carbon, i.e. having the same composition as pearlite.

When steel containing less than 0·85 per cent. of carbon cools through the re-heating point, ferrite is

naturally formed as well as pearlite, the composition of which never varies.

In the same manner, if the steel contains more than 0·85 per cent. of carbon, free carbide, or cementite, is eliminated as well as pearlite.

It must therefore be held that martensite, which approximately constitutes steel above 680°, first eliminates ferrite or cementite, thus attains to the percentage of 0·85 per cent. of carbon, and then becomes pearlite.

This hypothesis is suggested by the circumstance that pearlite, in non-tempered steel, is found united, in distinct masses, in the middle of ferrite or cementite, eliminated previously, like crystals in the middle of a mother-water.

The name hardenite, suggested by Howe for this special state of martensite, has no practical importance.

Graphite.—This appears in pure alloys containing more than 6·6 per cent. of carbon, and with a much lower percentage when silicium is present.

When the proportion of the latter is large the whole of the carbon assumes the form of graphite.

This is the characteristic constituent of ferrosilicium alloys, of grey cast-iron (Fig. 14) and of malleable cast-iron.

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CHAPTER VII.

DIAGRAM OF THE EQUILIBRIUM OF FERRO-CARBON ALLOYS.

AFTER dealing with the properties of the components, and before proceeding to the description, it is advisable to recapitulate the relation between the components, with the manner and conditions under which they enter into ferro-carbon alloys, by reproducing, in its entirety, Bakkhuis-Roozeboom's diagram of equilibrium. This shows the composition of the alloy for each pair of values of percentage in carbon, given as abscissæ, and of temperature, given as ordinates.

In the zone above A B C the metal is molten. In the zones A and B there is partial fusion, which renders portions of the metal liquid. Metal under these conditions changes considerably, and becomes what is commonly termed *burnt metal*. It is seen, moreover, that above 680° metal is made up of austenite, or γ iron holding carbon in solution.

The components not shown in the diagram, such as martensite, troostite and troosto-sorbite, are phases that apparently do not exist as such in natural metal, but are formed when special thermic treatment (tempering) destroys the equilibrium represented by the

diagram, tending to retain austenite at lower than normal temperatures. Given its tendency to transformation, this is only prevented in part; the re-

Fer-Carbone.
Carbon pour cent.
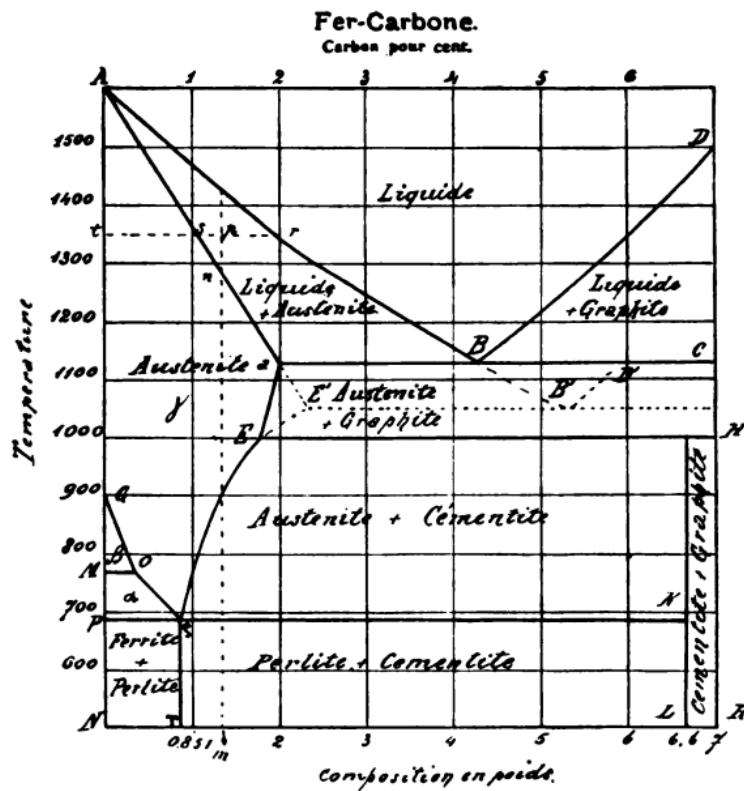
FIG. 19.

mainder gives the components mentioned, which may be considered intermediaries between austenite and pearlite.

Sorbite, which, as has been said, has the same

components as pearlite, only figures as a special form of the latter, produced when heating tends ·to reestablish the equilibrium broken by tempering, or when cooling is so rapid as to prevent the formation of the normal pearl-like structure.

Part O S T G has been shown before : it contains β iron, remaining in martensite.   Roozeboom's diagram is considered exact enough in the main, but this does not exclude partial rectifications.   Carpenter and Keeling have effected several, among them the raising of the fusion-point of pure iron to $1505°$.

Practical Applications of Metallography.—As may be seen from what has been said hitherto, metallography is capable of doing very useful practical service.   It lends itself to the investigation and control of all industrially treated and metallic alloys, since its methods of preparing and examining samples are applicable to all.

It has accordingly been tried on the most varied materials, but it finds its true application and its chief development in the study of iron and its alloys, cast-iron and steel.

These, indeed, are the products of the most widespread metallurgic industry and, on the other hand, they are the metallic compounds which present the greatest anomalies in the ratio between chemical composition and mechanical properties, which anomalies, as has been said, have brought the new method of investigation into being.

Metallographic laboratories now form a part of all the great metallurgical establishments, to test the outgoing products, and of the chief engineering works, as well as of the receiving department of many public offices, to examine the materials purchased.

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CHAPTER VIII.

MICROSTRUCTURE OF IRON.

THE definition of iron is :—

"The siderurgic products obtained in the soft state, decarburetting cast-iron in a reverberatory or low furnace, and afterwards working the bloom obtained with the steam hammer or in the rolling-mill."

The reverberating process is that known as puddling. The low furnace has almost entirely disappeared.

Iron produced thus contains a greater or less quantity of slag, which the hammer cannot entirely get rid of ; and its percentage of carbon is from 0·05 to 0·1 per cent.

Swedish iron, which is the purest, contains 99·8 per cent. of iron.

Micrographic examination is carried out by preparing a sample as described above, and acting upon the smooth surface by means of an 8 per cent. watery solution of ammoniacal chloride of copper, or of Kourbatoff's reagent.

The copper deposited is easily removed by means of a little concentrated ammonia.

With the microscope a structure mainly composed

Fig. 20.—Iron puddled and rolled in the direction of the arrow. Magnified 1100 diameters. Acted upon by Kourbatoff's reagent.

of ferrite polyhedra is observed (Fig. 20), and to this may be applied all that has been said with regard to the microstructure of pure metals. Very small quantities of pearlite are met with between the grains.

Moreover, a variable quantity of slag, chiefly silicates of iron and manganese, is found in the metal. Examining a sample cut from a plane parallel to the direction of the rolling, the slag appears in long strips, in the same direction (Figs. 20 and 21); cutting at right angles it appears in collected deposits. It is these strips of slag that give rolled iron its fibrous appearance, whence the iron itself was at one time thought to be made up of a sheaf of fibres. It is true that the grains of ferrite also lengthen in the direction of the rolling, especially if there is a large quantity of slag, but the lengthening is very slight, and the structure of the iron really remains granular.

The size of the grains increases with the temperature at which the cooling is begun and with its duration, according to the general rules of crystallogenesis.

Thus iron cooled slowly from 1000° (Figs. 21 and 22) shows much larger grains than the same when heated again at 900°, and quickly cooled by a blast of air (Fig. 23).

At one time, in consequence of a superficial organoleptic examination, a distinction was made between iron with a fibrous and a granular structure, and it was justly held that it could pass from the one to the

other.   But fibrous iron is merely that with fine grains, in which, as has been seen, stripes and layers of slag are most conspicuous.   When the crystals

$\longrightarrow$
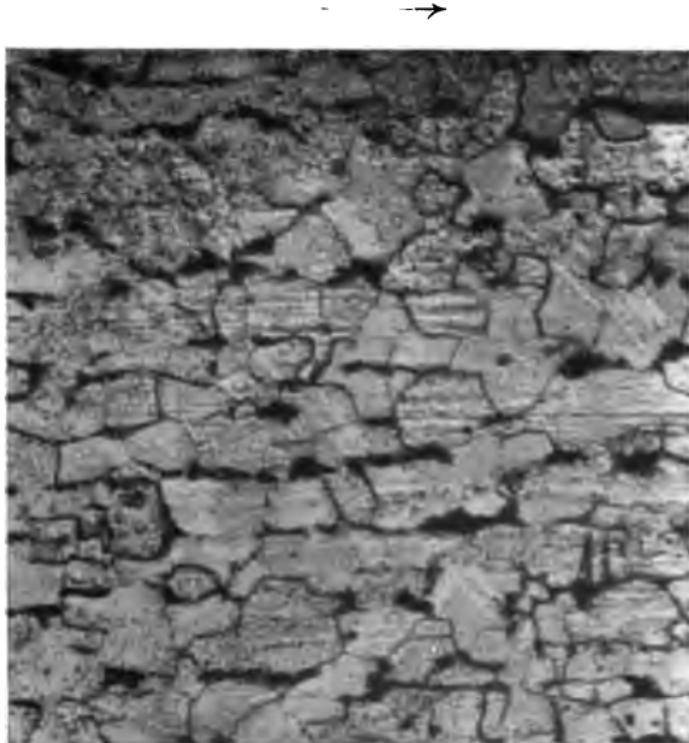
FIG. 21.—Rolled Iron, cut in the direction of the rolling. Magnified 300 diameters.   Acted upon by Kourbatoff's reagent.

become larger, on the other hand, their surface is more marked, and they stand out in the sample, which becomes granular.

From the earliest times it was believed that iron

having the latter structure, that of large grains, had
mechanical properties greatly inferior to those of the
iron called fibrous, i.e. having fine grains.   In the latter,
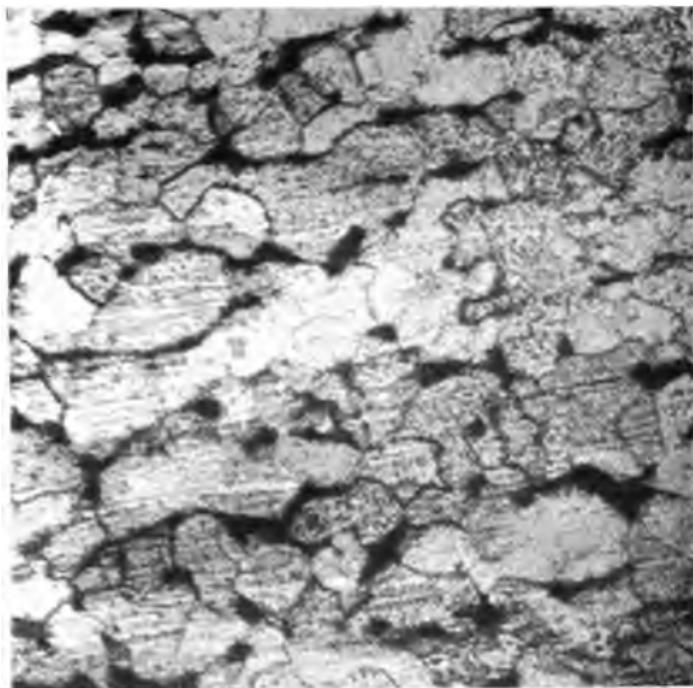
FIG. 22.—The same iron, cut at right angles to the direction of
    the rolling.   Magnified 300 diameters.   Acted upon by
    Kourbatoff's reagent.

indeed, the large quantity of grains and their smallness
produces a metal of greatly interwoven texture, increas-
ing the interlocking of the particles.   On the other
hand, the divisions between one crystal and another

in coarse-grained iron, owing to their large ˙surface, invite breakage, being, as it were, cleavage surfaces, which deprive the metal to a great extent of its power
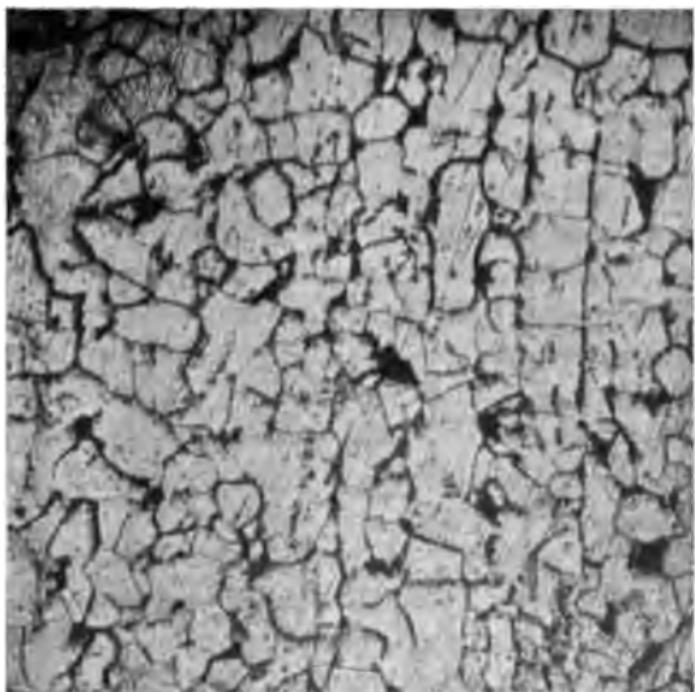
FIG. 23.—The same iron, annealed at 400° C.   Magnified 300
diameters.   Acted upon by Kourbatoff's reagent.

of elongation under traction and of resistance to sudden shocks.

From all this it will be seen how predominant a part the *size of the grain* plays in the technical valuation of iron.   Now this is not appreciable to the

naked eye except in very marked variations, but micrographic examination makes this criterion a very delicate means of judging, since it enables even small variations, and grades differing but slightly, to be recognised.

Although the *percentage of carbon* in iron is very small and of slight importance, the microscope is able to show on each occasion, without the necessity of laborious chemical analysis, that the sample does not contain abnormal quantities of pearlite.

Commercial iron, as is well known, is not fit to be tempered, since pure iron, passing through the change-points, transforms too quickly to be held fast by cold in the allotropic state due to a high temperature, and in this case the *proportion of carbon* is too small to have an appreciable effect upon the rate of trans-formation.

The *proportion of slag* can also be exactly gauged. It is inversely proportional to the resistance of the metal, since slag prevents the cohesion of the iron crystals between which it lies.

The presence or otherwise of *gaps* or *breaks in continuity*, which show the degree of finish in the mechanical elaboration, is revealed.

The microscope alone, again, can give an idea of the degree of transformation that has taken place in the grains of crystal during elaboration, or, as it has been called, the *hammer-hardening* of the metal. This deformation is especially produced when the metal is

cold wrought, and, when marked, greatly changes its properties, rendering it less ductile and much more brittle. Hence the best iron is that wrought hot and cooled to redness during elaboration. This possesses a fine and compact grain.

The tensional breaking strain does not vary much in different kinds of commercial iron, merely ranging from about 32 kilo. to 38 kilo. per square mm. but the elongation to which they can be subjected without breaking varies from 6 per cent. to 25 per cent. This shows the importance of the different determinations spoken of, which micrographic examination accomplishes easily and simultaneously.

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CHAPTER IX.

MICROSTRUCTURE OF STEEL.

THE definition of steel is :—

" The siderurgic products obtained in the liquid state by means of the Bessemer converter and those derived from it; of the Martin-Siemens reverberating furnace, of the crucible and of the electric furnace."

Alloys of iron, with all the elements which unite in them, are called steel, at least so long as iron prevails in them, and the proportion of carbon is not over 2 per cent. This is a conventional limit, as we shall see farther on.

Steel is divided into *carbon steel*, in which only iron and carbon prevail, and *special steel*, which also contains one or more other elements. As liquid preparation enables a considerable elimination of slag to be effected, a small proportion of them is a common feature in steel.

Both carbon and special steel, according to the treatment they undergo, are classed as follows :—

I. Crude ingot-steel.

II. Hammer-hardened steel.

III. Annealed steel.
IV. Tempered steel.
V. Softened steel.
VI. Cemented steel.

CHAPTER X.

CARBON STEEL.

THE micrographic examination of carbon steel, of all the kinds just mentioned, is accomplished in the manner already described.

A 5 per cent. solution of picric acid in absolute ethylic alcohol is employed for etching, or Kourbatoff's reagent, a 4 per cent. solution of nitric acid in amylic alcohol. For very soft steel, a watery 8 per cent. solution of ammoniated chloride of copper is also used to advantage.

Crude Ingot-Steel.—This name is given to steel obtained by simple solidification of the liquid metal and slow cooling.

Steel is thus formed under the same conditions as rock, evolved from fluid. The different components are deposited separately, the less fusible first, the more fusible later, in the interstices left by the former and around their crystals. A state of complete equilibrium is obtained.

Such steel, owing to the slowness of cooling, for instance in a mould, has large elements, and is therefore rather brittle, so much so that in steel foundries,

as we shall explain later, the castings taken from the
moulds are subjected to further processes.

Steel with less than 0·5 *per cent. of Carbon.*—Steel,
according to the modern definition, may have the
same percentage of carbon as commercial iron, i.e.
less than 0·1 per cent.

It is differentiated from it by the total absence of
slag in layers and by the very small quantity of
slag in lumps. The grains are not in the least
degree deformed.

The structure is similar to that described in the
case of pure metals, and is made up of large polyhedra
of ferrite, intermingled with pearlite.

Since this more fusible component has 0·85 per
cent. of carbon, the molten metal remains liquid in
spite of the lowering of the temperature, separating
itself by degrees from the carbonless ferrite. It crys-
tallises in the mass, and when, by concentrating, it has
attained to the composition of pearlite, it solidifies as
such in the interstices left between the ferrite crystals.
Pearlite in steel below 0·5 per cent. contains the whole
of the carbon in the metal.

Our photographs represent a series of steels with
increasing percentages of carbon. It may be seen how
pearlite, as a necessary consequence, increases from
one to the other.

Since we know that in steel with less than 0·5 per
cent. of carbon there is none of it in the ferrite, and
that pearlite contains 0·85 per cent. of it, a simple

planimetric sketch on the photograph of the sample
will show the ratio between the total area and that
occupied by the pearlite, and thus enable the propor-
tion of carbon in the steel to be determined exactly.
An expert metallographer, by merely looking through
the microscope, without an eyepiece micrometer, can
easily tell the percentage of carbon to within 0·5 per
cent. The less experienced student can prepare photo-
graphs of a set of steels of known ascending percent-
ages, say by increases of 0·1 per cent., and thence form
a judgment as to that submitted to him.

Now the quantity of carbon contained in any steel
has a direct and considerable influence upon its me-
chanical properties.

This principle is illustrated by our photographs,
which are of industrial steel, prepared by ourselves in
the Martin furnace or the converter.

Steel at 0·18 per cent. of carbon (Fig. 24) has
given, as strain of extension, R = 41 kilo. per square
mm., and 25 per cent. of elongation before reach-
ing breaking point, in a small sample 200 mm. long.
It is an open-hearth steel.

Steel with 0·262 per cent. of carbon (Fig. 25),
obtained by the Bessemer process, already shows
a quantity of pearlite much larger than the last.
It has given, as strain of extension, R = 47 kilo.
per square mm. and, as elongation, A = 23 per cent.

Steel with 0·36 of carbon (Bessemer) shows
(Fig. 26) a considerable quantity of pearlite. It has

given $R = 54$ in strain of extension, and $A = 21$ per cent. in elongation. Steel with o·455 per cent. of carbon (Fig. 27) shows, in the photograph, the
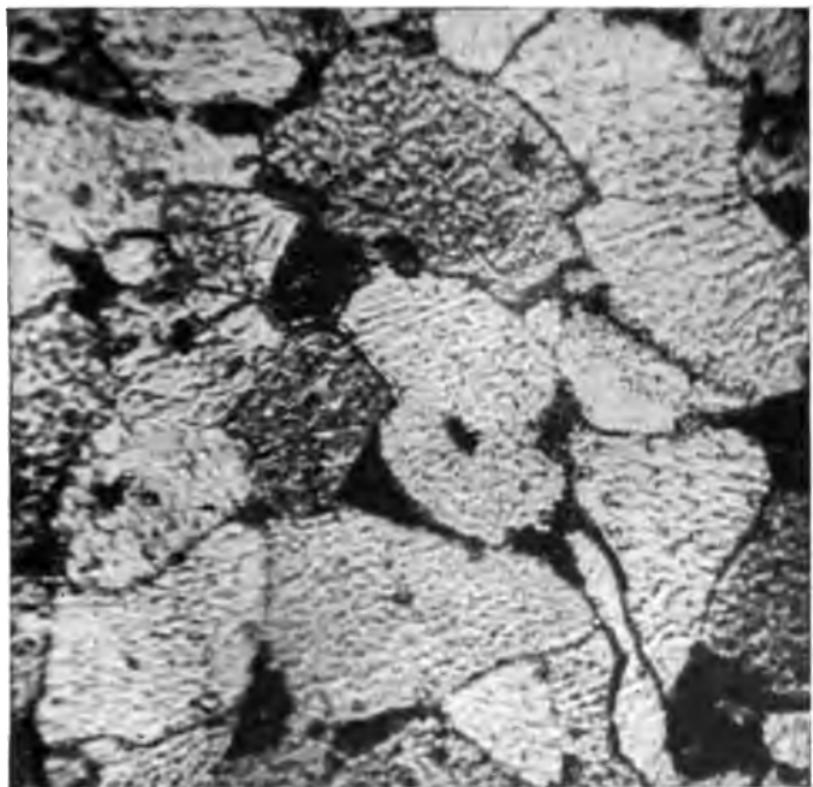
FIG. 24.—Magnified 650 diameters. Crude Steel with o·18 per cent. carbon. Acted upon by 8 per cent. ammoniated chloride of copper.

structure of steel cast at too high a temperature, and therefore with a very coarse structure. It is an open-hearth steel, run into an earthen mould at a tempera-

ture of about 1650° (determined by Wauner's optic pyrometer and by Wiborg's "bombs"). It has given R = 59, and A = 18 per cent. Owing to the conditions in which it was cast, without being given time
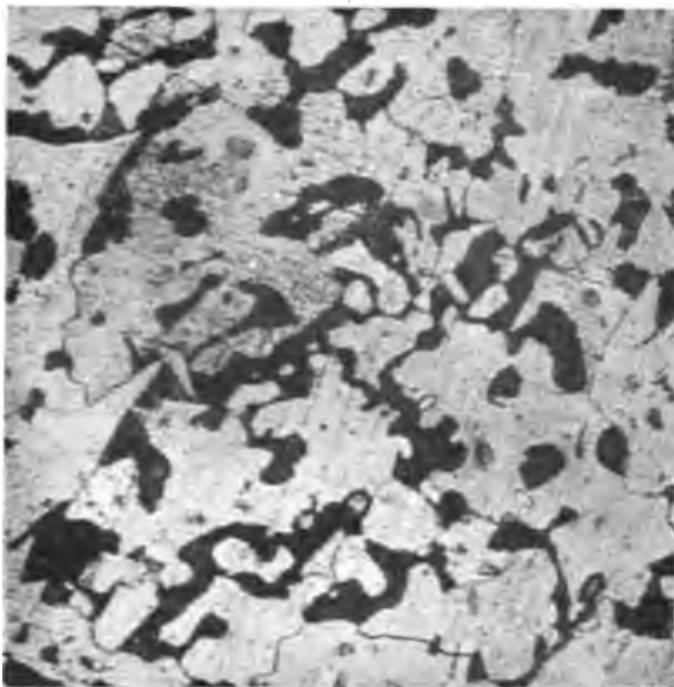
FIG. 25.—Crude Steel with 0·262 per cent. carbon. Acted upon by Kourbatoff's reagent.

to rest, it carried with it slag (silicates of iron and manganese), which is seen in the ferrite. To free the metal from this slag, which seriously interferes with the quality of the castings and the bars, it is usual to

gather the product run from the furnaces in well heated ladles, and to let the steel rest for some time. The slag, which is lighter, is thus enabled to rise to the
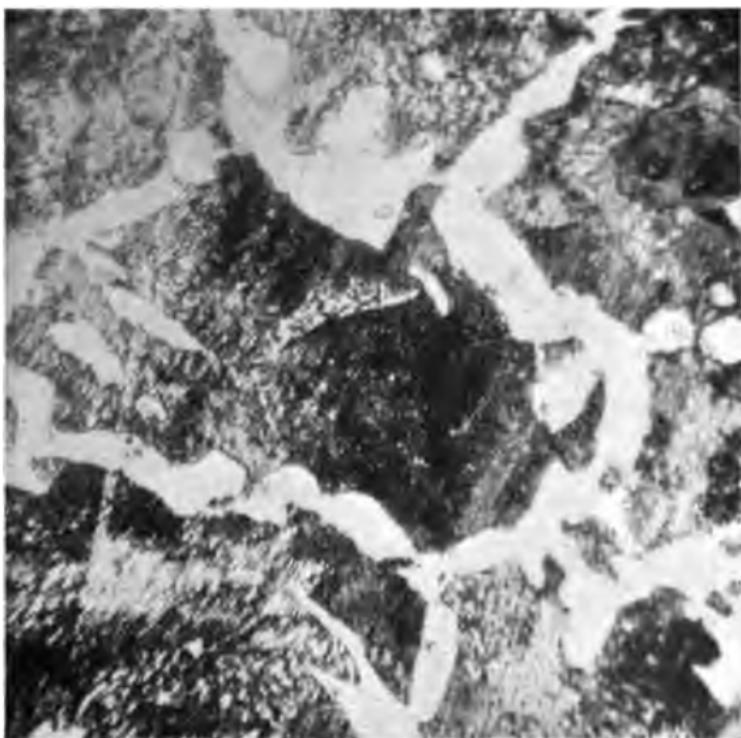
FIG. 26.—Crude Steel with 0·36 per cent. carbon. Magnified 650 diameters. Acted upon by Kourbatoff's reagent.

surface, where it forms a thick layer, which serves to protect the metal from irradiation, and can afterwards easily be removed.

To this end it was recently proposed to apply the

electric furnace, which is still generally too costly to work for it to be suitable for the whole process of fusing. The suggestion made was that the steel should be prepared according to Bessemer's or

FIG. 27.—Crude Steel with 0·455 per cent. carbon. Magnified 550 diameters. Acted upon by Kourbatoff's reagent.

Martin's method, and should afterwards be poured into an electric furnace of any kind—preferably inductive—and left for an hour. Here the steel would remain quite still and free from all oxidising action,

so that the whole of the slag would separate from it and no more would be formed, whilst, on the other hand, the temperature of the metal could be raised or kept stationary at will. Under such conditions, moreover, sulphur would be almost completely absorbed by manganese, and be eliminated with the slag.

We have noticed an increase from one steel to another in strain of extension, with a corresponding decrease in elongation, proportional to the greater percentage of carbon. These two physical phenomena are the practical features in steel upon which metallurgists and manufacturers base their conclusions. The percentage of carbon, therefore, to a great extent represents the quality, and constitutes the commercial value of the product.

This percentage, as has been seen, is quickly revealed by micrographic examination, the process of preparation lasting, on the whole, about 20 minutes, whereas chemical analysis would require several hours, including the time necessary to prepare the sample.

But the microscope, without further loss of time, also shows if there are other substances which can influence the quality of the metal, such as slag, as has been shown in the last example. It is evident, on the other hand, that the chemical determination of such small quantities of silicates would involve great expenditure of time and labour, with small probability of accurate results, seeing that several of the sub-

stances contained in slag are also found, though in other forms, in steel.

The microscope also furnishes the means, not otherwise attainable, of knowing the structure of the metal, as we shall see when we treat of annealing, of finding out the existence of cavities, inclusions of all kinds, sand holes, and similar heterogeneities.

A very useful application of micrography is the testing of the products from the Martin furnaces; whence metal is taken that has been cast in a greater or less state of decarburation, according to the hardness required, a feature in the steel varying with the purpose for which it is to be used.

In order to discover if the metal in the furnace has reached the requisite degree of carburation, a sample is usually taken out, is cast in the form of a small sample, and its behaviour under the blows of a steam-hammer is observed. A highly skilled worker may form a sufficiently correct opinion from the phenomena of malleability or fragility which he notices, but this method is empirical in itself, and it is difficult to find a foreman who can invariably use it with good results.

Chemists have made attempts rapidly to gauge the carbon in the least possible time, but this has always been longer than the time allowed for carrying on the work.

Instead of this a small sample can be cast, a smooth face can be cut upon it at once with the help of the

mechanical appliances available in large workshops, it can be polished, even if not completely, and examined under the microscope.

With the criteria and the approximation above described, the foreman can be quickly enlightened as to the real quality of the metal he is dealing with.

This operation, when everything is held in readiness, never takes more than a quarter of an hour.

Metal can easily be kept meanwhile in the furnace, under practically constant temperature and composition, it being only necessary to regulate the quantity and ratio of gas and air in the flame.

Steel up to o·5 per cent. of carbon practically comprises the following categories:—

I. *Extra Soft Steel*, up to o·2 per cent. of carbon, which cannot be tempered, is mild, like iron, and is also called homogeneous iron. It is used for boiler plates and electrical machines, for cementing or forging pieces, for nails, bolts, boiler tubes and the like.

II. *Soft Steel* from o·2 per cent. to o·35 per cent. of carbon, which is not very susceptible to soldering or tempering, and is used up to o·25 per cent. for structural iron, plates and Navy steel, and, from o·25 per cent. to o·35 per cent. for forgings, shafts, rods, axles, small rails, and for the casting of pieces liable to shock, such as railway material.

III. *Half Hard Steel*, from o·35 to o·5 per cent. of carbon, capable of being tempered, but not weld-

able, used for castings, shafting, bearings, axles, ordinary cutlery, and weapons.

Steel from 0·5 *per cent. to* 0·85 *per cent. of Carbon.* This is made up of the same elements as that with the lower percentage and the quantity of pearlite grows with that of carbon, but at a slower rate.

It has been mentioned, indeed, in connection with ferrite, that in such steel it keeps 0·27 per cent. of carbon in solution, whereas, in those with a smaller percentage, the whole of the carbon is contained in pearlite, under the form of carbide. It follows that in steel with 0·5 per cent. or more the proportion of pearlite is relatively less, since ferrite, eliminated first, has already carried away part of the carbon.

Guillet observed steel containing 0·55 per cent. of carbon with the planimeter and found that the area occupied by the pearlite was about $\frac{45}{1000}$ of the whole. Now, if we calculate the area of the pearlite as it would be if ferrite contained no carbon, we obtain $\frac{65}{1000}$. If, instead, we suppose that ferrite contains 0·27 per cent. of carbon, we get $\frac{48}{1000}$, a figure much nearer that given by actual observation, and sufficiently near for all practical purposes, especially considering the difficulty of planimetric sketching under such conditions, and the inevitable divergences presented by chemical analysis.

The exact gauging of the percentage of carbon in

such steel is, for the reasons given, a little slower, but it can always be satisfactorily performed when 0·27 per cent. of carbon is deducted as being dissolved in ferrite.
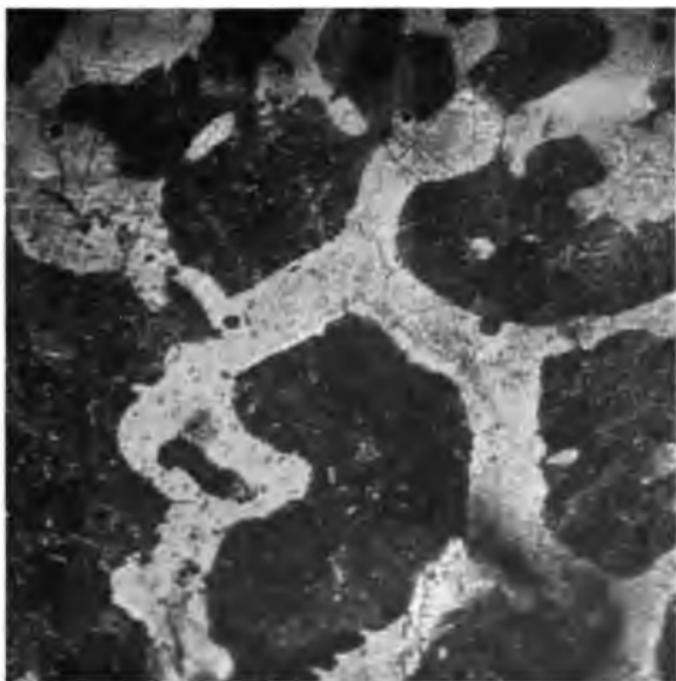

FIG. 28.—Crude Steel with 0·52 per cent. carbon. Magnified 300 diameters. Acted upon by Kourbatoff's reagent.

Steel with 0·52 per cent. of carbon (Fig. 28) gave :—

$$R = 63$$
$$A = 12 \text{ per cent.}$$

The last figure is much lower than the mean in steel, having the same percentage of carbon. This is due to the coarse structure of the metal, well repro-
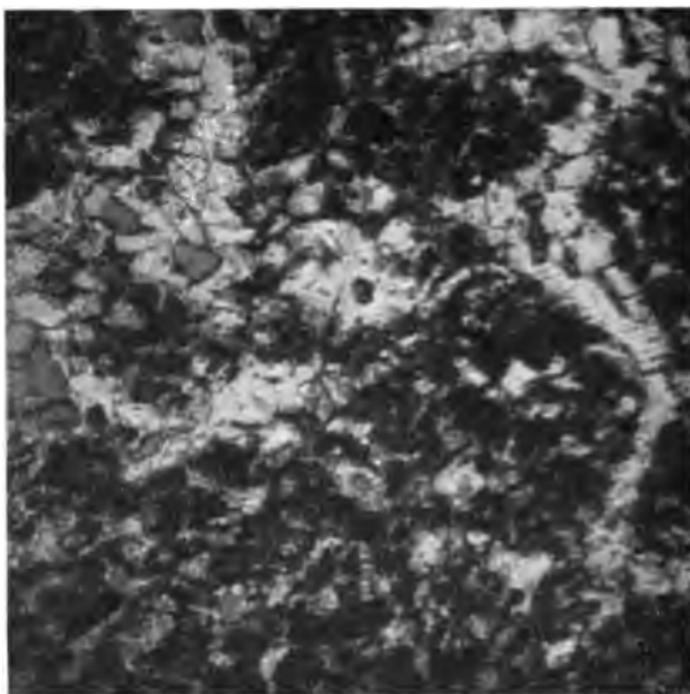
Fig. 29.—Crude Steel with 0·618 per cent. carbon. Magnified 300 diameters. Acted upon by Kourbatoff's reagent.

duced in the photograph, and caused by too hot casting. The steel wheel from which the sample was taken, indeed, split when tested, bearing out the predictions of metallographic examination.

Steel with 0·618 per cent. of carbon (Fig. 29) gave :—

$$R = 70$$
$$A = 14 \text{ per cent.}$$
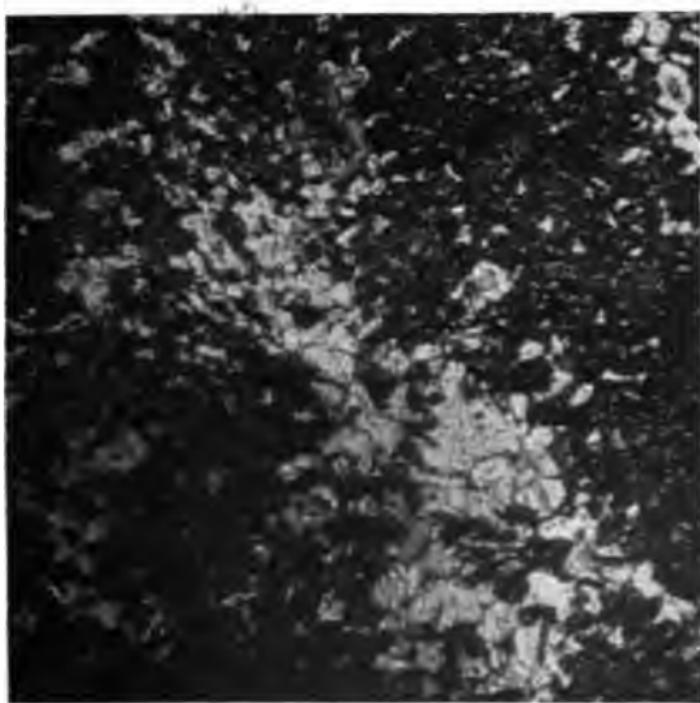
FIG. 30.—Crude Steel with 0·685 per cent. carbon. Magnified 300 diameters. Acted upon by Kourbatoff's reagent.

It is seen, on comparison with that preceding, how fineness of structure prevails over percentage of carbon as regards elongation. Here, too, a certain amount of slag is visible.

G

Steel with 0·685 per cent. carbon (Fig. 30) gave :—

$$R = 74$$
$$A = 12 \text{ per cent.}$$
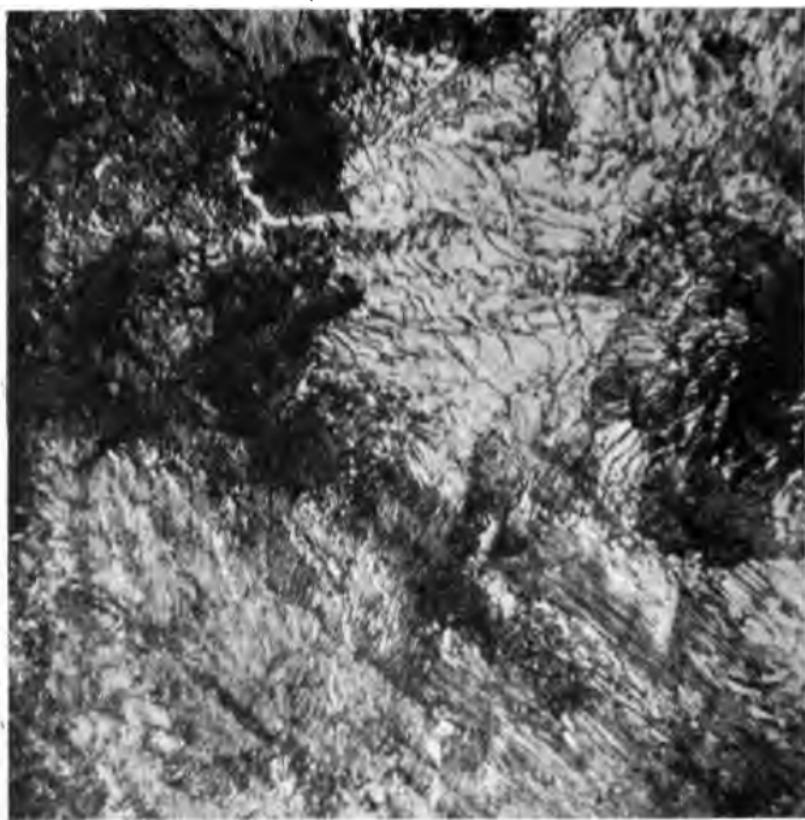
FIG. 31.—Crude Steel, C = 0·75 per cent.　Magnified 650 diameters.　Acted upon by Kourbatoff's reagent.

We see the proportion of pearlite increase constantly, until it occupies the greater part of the sample.

For steel with 0·75 per cent. carbon (Fig. 31) ferrite is only seen in little zones scattered here and there in the pearlite.

This steel represents :—

$$R = 82$$
$$A = 11 \text{ per cent.}$$

The great purity of this steel, cast after standing a long time, allowed it to give a very satisfactory elongation, considering its hardness.

Steel from 0·5 per cent. to 0·85 per cent. includes the following categories :—

I. *Hard Steel*, from 0·5 per cent. to 0·7 per cent. This can be strongly tempered, and is used for castings (with 0·25 to 0·4 per cent. of Si. and 0·55 to 0·7 per cent. of Mn), for rails, springs, cable wire, blades for paper, hammers, sledges, wedges, punches, tyres, mining bars, scythes, files, knives and tools.

II. *Very Hard Steel*, from 0·7 per cent. to 0·85 per cent. of carbon, used for spheres for mills, files, saws, railway switches, specially strong springs, tools in general, center punches, milling-cutters, and fine cutlery.

Steel with 0·85 per cent. of Carbon.—Since pearlite, as has been seen, contains 0·85 per cent. of carbon, steel with this percentage is composed exclusively of pearlite. This is the so-called euthectic steel (Fig. 32).

Sometimes a small quantity of sorbite, i.e. of pearlite with its components blended, is met with in this steel, probably because it has been compressed

by the remainder and prevented from crystallising properly.
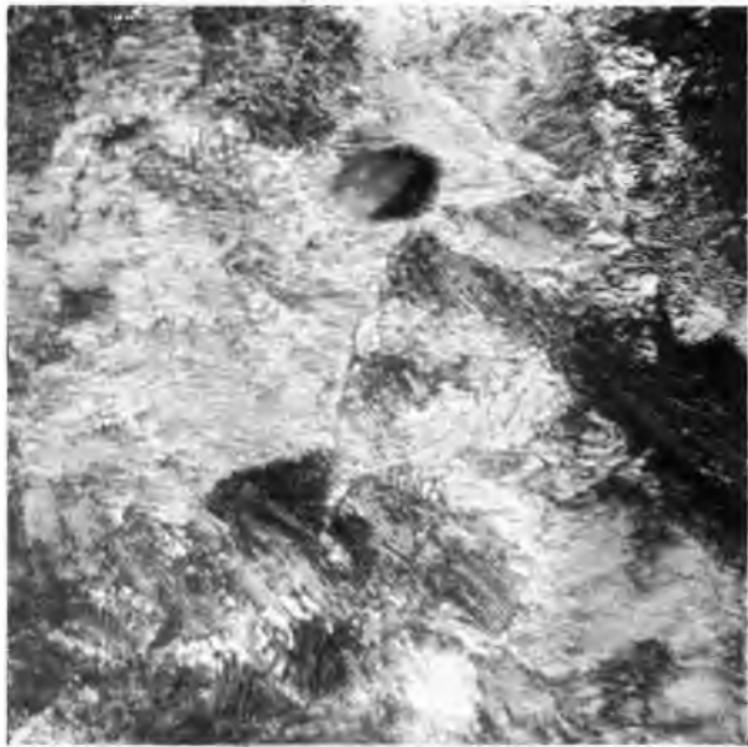

FIG. 32.—Crude Steel, C = 0·88 per cent. } Magnified 650 diameters. Acted on by 5 per cent. picric acid in ethylic alcohol.

It furnishes the following mechanical figures :—

$$R = 95 \text{ to } 100$$
$$A = 5 \text{ to } 4 \text{ per cent.}$$

The last category, that of *extra hard steel*, begins with euthectic steel having 0·85 per cent., which is especially used for tools, for cable strands of high tensile strength, for rolling cylinders and for certain parts of spinning machinery.

Steel with more than 0·86 *per cent. of Carbon.*—In order to reach the degree of concentration of pearlite, cast metal containing over 0·75 per cent. of carbon must eliminate carbon, not ferrite, and does so under the form of carbide, or cementite.

Steel above 0·85 per cent., or *hypereuthectic steel*, is therefore made up of pearlite and cementite. This is either in isolated crystals, surrounded by pearlite, or, as the ratio of carbon increases, forms a network dividing the mass of pearlite.

Cementite, on account of its high proportion of carbon (5·67 per cent.), must always be found in steel in lesser quantities than pearlite, since steel, in order to be such, cannot contain more than 2 per cent. of carbon.

The ordinary action by means of picric or nitric acids gives pearlite the same appearance both in hypoeuthectic and hypereuthectic steel, while the ferrite and cementite become equally white. This may lead to doubts, especially when, at temperatures near that of euthectic steel, they are met with in small crystals whose form is not well defined.

In such cases it suffices to burnish the sample again with alumina, in order to obliterate the action of the

acid, and to boil it in a 25 per cent. solution of caustic soda, to which 5 per cent. of picric acid has been added. Any cementite there may be becomes black, while the rest remains unaltered ; its presence is thus made known and excludes that of ferrite. An experienced observer, however, can distinguish the two constituents by means of the ordinary reagents.

Cementite is brilliant and compact, and remains in relief even after prolonged action, without showing either polyhedric structure or dividing lines, whilst ferrite, under similar conditions, darkens slightly, becomes concave and divides into grains.

The steel with 1·1 per cent. of carbon shown in Fig. 33 was acted upon by picrate of soda. The black network is formed by cementite : the rest of the metal, consisting of pearlite, has remained unaffected by the action of the picrate.

Steel with 1·717 per cent. of carbon was obtained in the converter by stopping its operation long before decarburation was completed. This steel was acted upon by Kourbatoff's reagent, and therefore shows cementite white and pearlite black (Fig. 34).

The same, more highly magnified (Fig. 35), confirms what has been said as to the appearance of the cementite. The only valuable property in these extra-hard steels is their hardness, owing to which alone they are used for mining drills, exploding projectiles and the like.

Their tensional breaking strain is very high, but

they are hardly capable of any elongation and this excludes them from being put to any other uses than those mentioned.
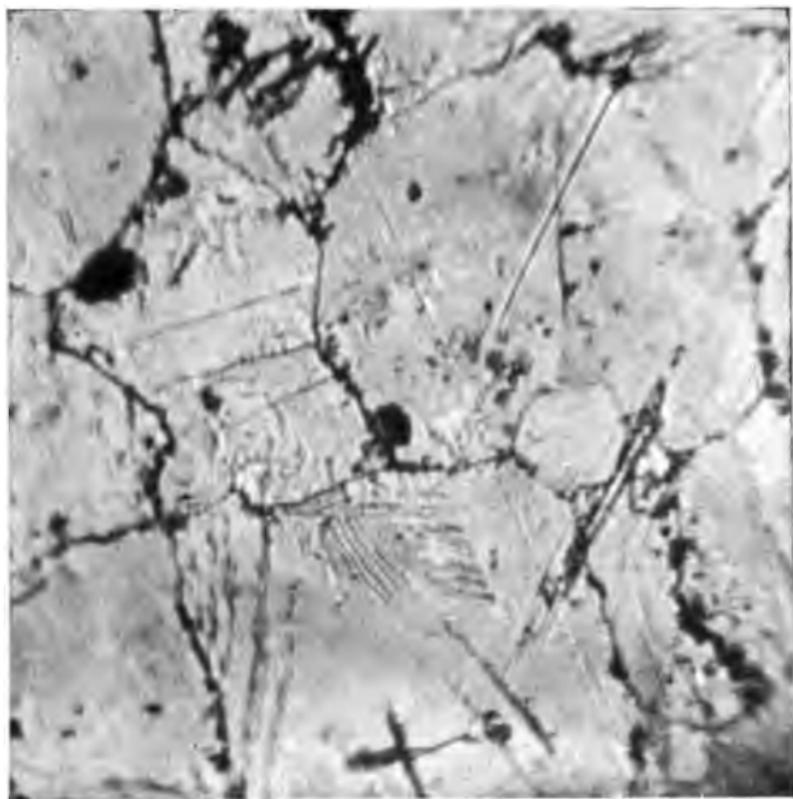

FIG. 33.—Crude Steel, C = 1·1 per cent. Magnified 650 diameters.
Acted upon by picrate of soda.

Near the conventional limit between extra-hard steel and cast-iron, i.e. between 1·8 per cent. and 2

per cent. of carbon, is the steel from which fire bars are cast, called by some steely cast-iron.   These bars cannot be of cast-iron, because they would be too brittle
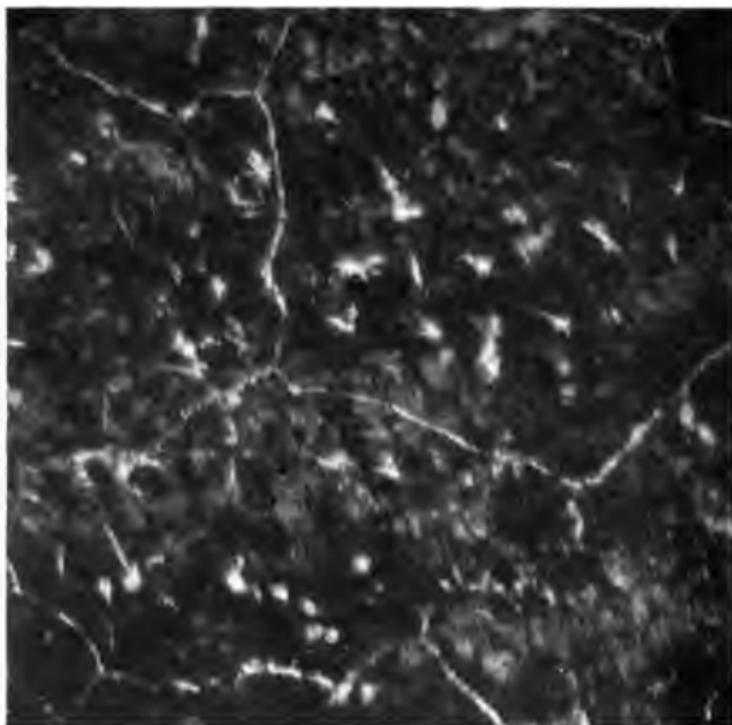

FIG. 34.—Crude Steel, C = 1·717 per cent.   Magnified 150 diameters.   Acted upon by Kourbatoff's reagent.

and fusible ; besides, they must contain enough carbon to be hard and to stand wear.

In concluding our review of crude ingot-steel, we

may mention that it is easier to obtain good castings, without cavities or bubbles, in proportion as the percentage of carbon is high. As this increases, in fact, the metal remains molten at an even lower temperature, and
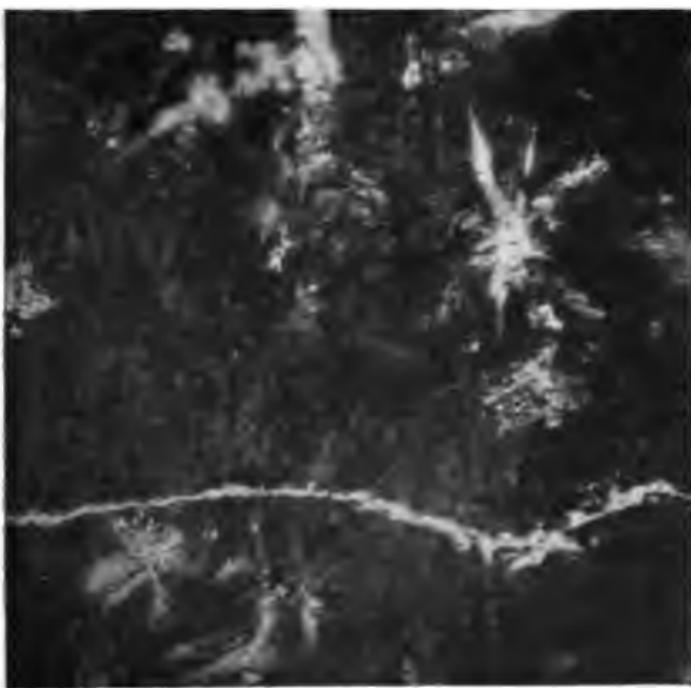

FIG. 35.—The same as Fig. 34, under a more powerful magnifier. Enlarged 650 diameters.

its perfect fluidity on entering the mould is the better guaranteed. Moreover, as decarburation—which generally takes place in the converter, or in the bottom of the open-hearth, owing to the action of air—has not

been carried to too great a length, the steel does not contain oxide of iron and there is no danger that the latter, forming oxide of carbon within the liquid, should cause bubbles of gas, or blowholes, so harmful to the success of the casting.

Hammer-hardened Steel.—Steel which has undergone mechanical elaboration with the steam hammer, by rolling, or in wire-drawing mills, presents structural varieties, due to change of form and volume brought about by the elaboration.

Suppose steel be heated to about the re-heating point (680°) and wrought up to the exact moment when, while cooling, it reaches this point. During the high temperature the rest necessary for the formation of large crystals will be wanting, and, when the violent strain is over the change-point will be past, so that the constitution of the steel will no longer be subject to change.

Steel thus treated will have the best of structures, being made up of very fine grains, without cavities or breaks in continuity. But in practice this can only be a special case, attainable as an exception. Usually the elaboration stops either above or below the change-point.

If above, large crystals have time to form, at least in the centre of the piece, and the metal, on account of the size of its elements, is brittle, resembling raw cast-steel in structure.

If below, the grains already formed lose their shape,

are crushed and, remaining in a state of strain, render the metal brittle. When thus changed by being wrought below the critical point it is called *hammer-hardened*.
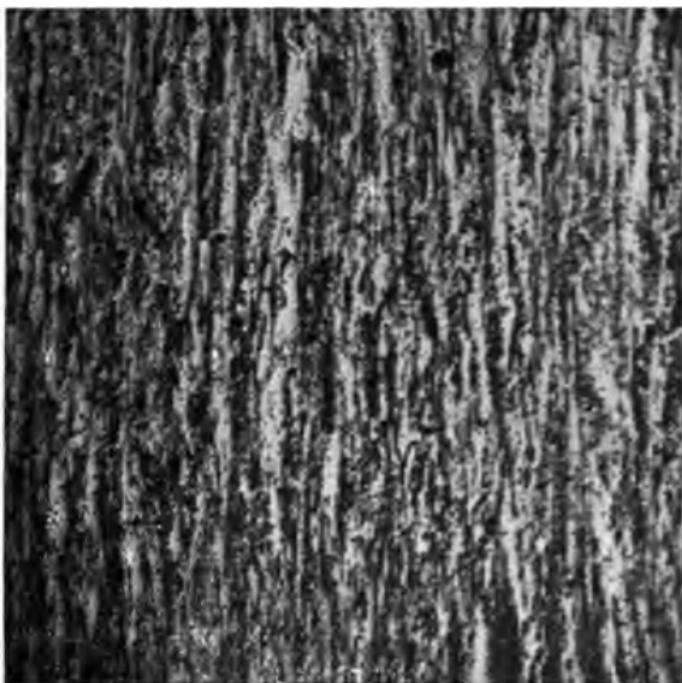

FIG. 36.—Hammer-hardened steel, C = 0·46 per cent. Magnified 300 diameters. Acted upon by Kourbatoff's reagent.

We show a very marked case of hammer-hardening in steel passed through the screw-plate at too low a temperature (Fig. 36). It contains the usual components of steel, but lengthened and, as it were, disintegrated, in the direction of the strain suffered.

The photograph is that of a strand belonging to a telephonic cable, which broke as soon as it was put in action, without any apparent reason.

The strand, taken from a wire rope, was soldered with tin in a longitudinal cavity hollowed in another piece of steel, so as to be polished and prepared in the usual way. The microscope clearly revealed the cause of the breakage, which was due to the easily visible deformation created by careless manufacture.

In the next chapter we shall see the remedy for such cases of brittleness.

Annealed Steel.—Steel is termed annealed when it has been carried to a temperature higher than the re-heating point, and has been allowed to cool naturally.

Annealed steel has the same components as crude cast steel, but its structure is much finer, since its cooling began at a temperature little higher than the re-heating point, while the cooling of cast steel begins at the temperature of liquid metal poured into moulds (about 1500°).

Moreover, as founding moulds are very restrictive, cooling in them is slow, and large crystals, a cause of brittleness, are developed in the metal.

Instead of this, during the operation of annealing the cooling takes place faster, and there is thus another cause of smaller structure.

Steel castings are, therefore, usually submitted to

annealing in practice, in order to eliminate brittleness. The piece is heated to between 800° and 900°, by which means the pre-existing structure is destroyed through passage across the change-point. Then the
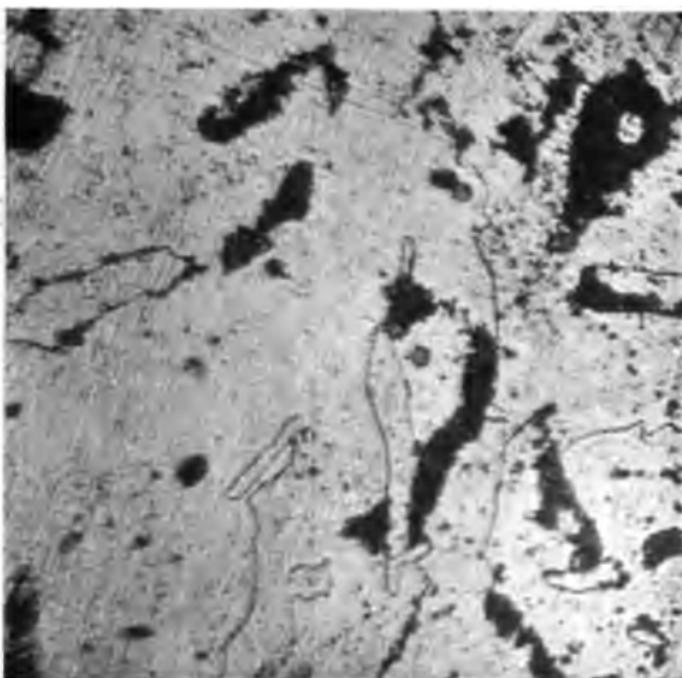

FIG. 37.—Crude Steel (brittle), C = 0·182 per cent. Magnified 300 diameters. Acted upon by Kourbatoff's reagent.

piece is taken out of the furnace and allowed to cool in the air.

We give two photographs of the same steel, having 0·182 per cent. of carbon, and taken with the same

magnifier, the one after casting, the other after the annealing just described (Figs. 37 and 38).

Hot wrought steel, as has been said, if finished at a high temperature, may be compared to crude cast-steel,
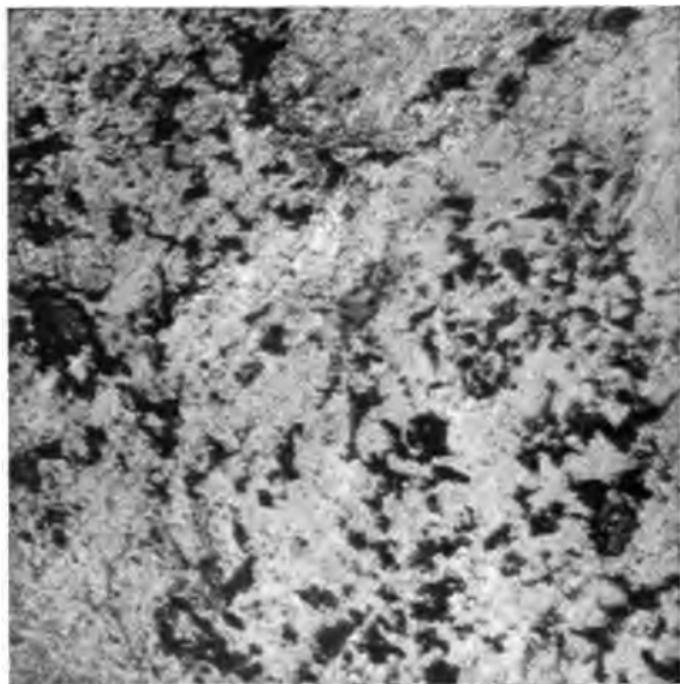

FIG. 38.—The steel is Fig. 37, annealed at 900°.
Magnified 300 diameters.

though it is never so coarse. It, too, is annealed, with similar results (Fig. 39).

Annealing is also practised in the case of cold-wrought or *hammer-hardened* steel whose elements are

changed and deformed. A normal structure can thus be regenerated in it, and brittleness avoided.

It must be observed that in annealing a certain amount of carbon is always lost, at least in the super-
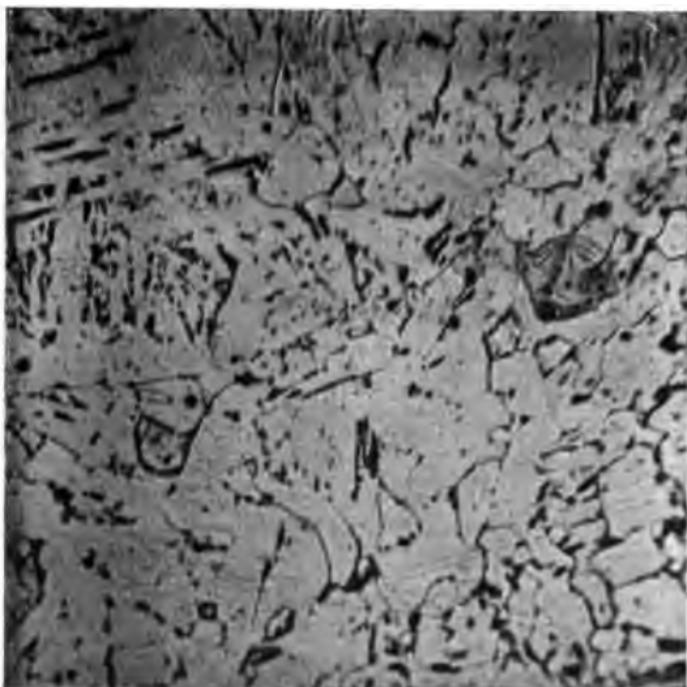

FIG. 39.—Extra Soft Steel, hot-wrought and finished, and afterwards annealed at 900°. Magnified 150 diameters. Acted upon by Kourbatoff's reagent.

ficial strata, owing to the oxidising action of air at a high temperature.

If the cooling is very rapid a certain quantity of

sorbite is produced on the surface, and, as this is harder than pearlite, it gives the surface greater hardness. This fact has been made use of, as mentioned above, in making rails, which are allowed to cool quickly on purpose to create a sorbitic crust that will increase their wearing capacity.

Tempered Steel.—Tempered steel is defined as that which, under ordinary temperature, shows a constitution similar to that ordinarily stable only at a high temperature, this structure having been kept in it by sudden cooling, through special agents, whilst it was above the re-heating point.

Steel cannot therefore be tempered except above 680°. A certain proportion of carbon is required, since, as has been said, it tends to bring about and to maintain the formation of γ iron, in which it is highly soluble, hinders allotropic transformations in a downward direction, and delays them, giving time to the sudden cooling to stop them altogether.

Hence steel takes tempering easily and markedly in proportion to the carbon it contains, whereas commercial iron and steel below 0·2 per cent. of carbon do not take it at all, their transformations being too rapid.

Ordinary Tempering.—This is effected by heating steel between 700° and 800°, so that the whole mass is equally and uniformly penetrated by the heat, and then plunging it into cold water, which must be in such proportion to the metal as not to suffer any appreciable rise in temperature.

Different baths, such as acids, saline solutions, mercury, etc., have been used, but in our day greater

FIG. 40.—The same steel as in Fig. 26, C = 0·36 per cent., annealed at 900°. Magnified 650 diameters. Acted upon by 8 per cent. ammoniated chloride of copper.

importance is attached to the caloric capacity than to the conductivity of the bath, and water is considered the best.

H

Steel tempered under these conditions is completely transformed into martensite.

Our photographs (Figs. 41 and 42) show different
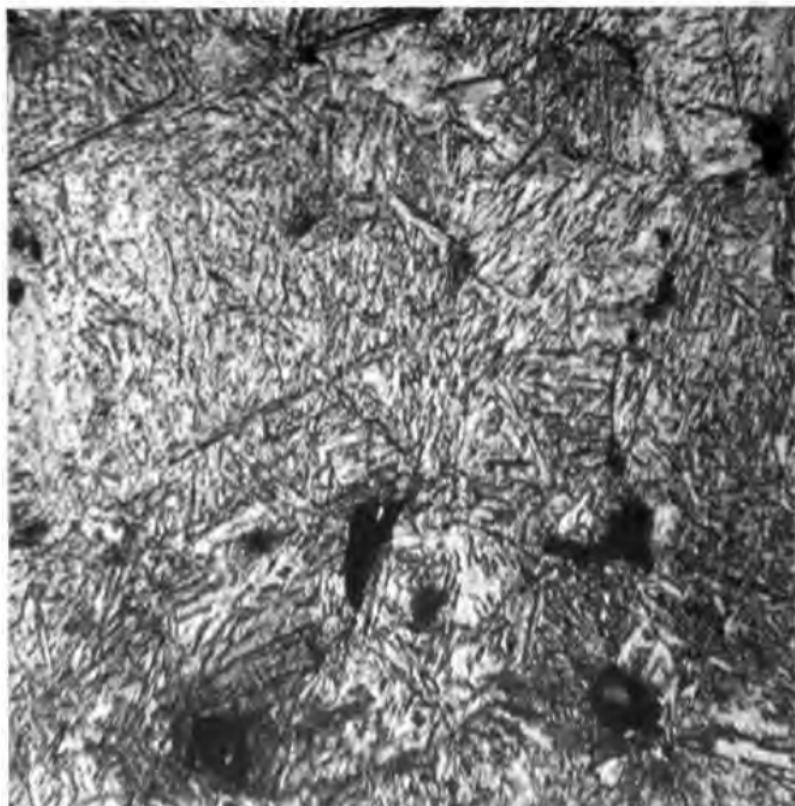
Fig. 41.—Steel tempered at 800°, in water.   Magnified 650 diameters.   Acted upon by Kourbatoff's reagent.

aspects of tempered steel.   It may be seen how tempering gives them an appearance strikingly different

from that which they had before. This appearance is the most characteristic effect of tempering, and therefore the microscope is by far the best judge of its success.

FIG. 42.—75 per cent. steel, tempered at 800° in water. Magnified 650 diameters. Acted upon by Kourbatoff's reagent.

Micrographic investigation alone, moreover, by means of its intimate dissection of components, has enabled the idea of tempering to be clearly understood,

and has revealed the true nature of the phenomenon. Until recently this was still obscure, and formed the subject of the most dissimilar theories.   Practical men,
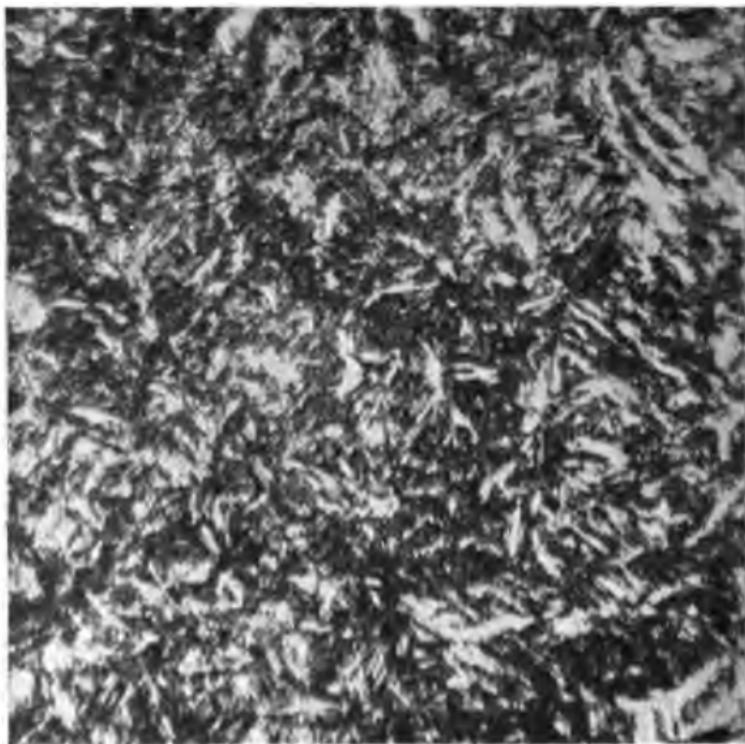

FIG. 43.—Steel with 0·85 per cent. carbon, tempered at 800°
        in water.   Magnified 650 diameters.   Acted upon by
        Kourbatoff's reagent.

again, not knowing the causes, found it hard to obtain the effects.   Tempering was an operation whose result was always uncertain, especially with the varying of the

material submitted to it. Now, on the contrary, there
are very clear rules, and the microscope affords a certain
check.

Ordinary tempering, as is well known, renders
metal hard, for the reasons given when speaking of
martensite.

Steel with 0·85 per cent., tempered (Fig. 43), is
said to be composed of that kind of martensite which
was called hardenite for some time.

Soft Tempering.—This is obtained when tempering
is effected under modified conditions, e.g. when steel
is tempered whilst it is exactly at the change-point, or
when, being heated a little more, it is plunged into a
bath, less active than water, such as oil or molten
lead.

Steel thus tempered still contains martensite, but
it is characterised by a greater or less quantity of
troostite, which appears black, whereas the martensite
remains white (Fig. 44).

Soft tempering gives less than ordinary hardness,
and is sometimes used for this reason. In such cases
the presence and quantity of troostite will have to be
checked.

If, on the other hand, troostite is found in steel
submitted to ordinary tempering, this shows the opera-
tion to have been unsuccessful, and it must be repeated,
the temperature of the heating furnace and of the tem-
pering bath having first been examined and adjusted.

Sharp Tempering.—This is obtained by exaggerat-

ing the conditions of tempering, i.e. by taking steel with over 1·1 per cent. of carbon, heating it above 1000° and plunging it into a bath below freezing-point.
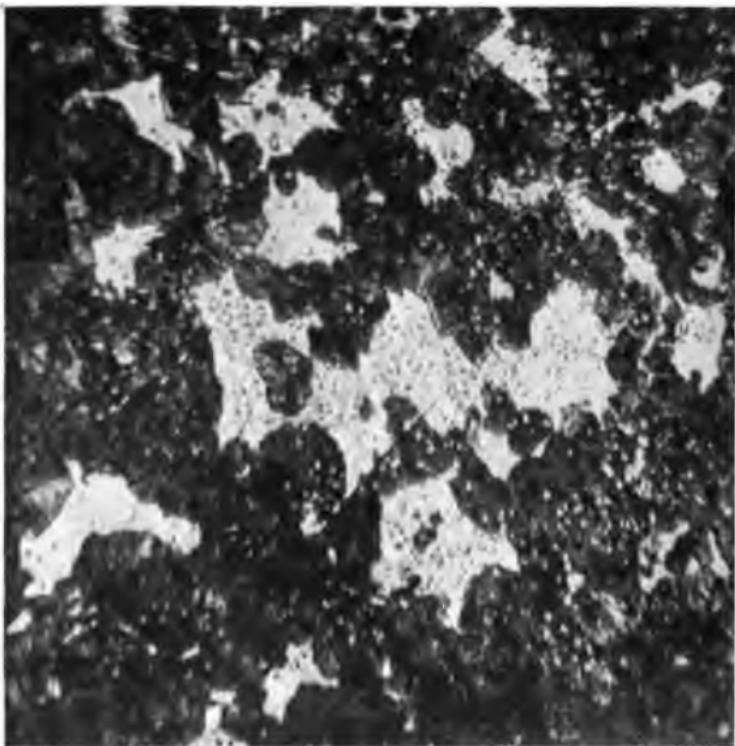

FIG. 44.—Steel with 0·7 per cent. carbon, tempered at 680° in water. Magnified 650 diameters. Acted upon by Kourbatoff's reagent.

Such tempering is characterised by the disappearance of austenite and troosto-sorbite. The former increases with the percentage of carbon; the latter is found with

a little martensite, in the shape of arrow heads, in the middle of the austenite. This tempering has no practical value.

Softened Steel. —Tempered steel is called softened when it has been heated, not however up to the change-point, and then allowed to cool. Austenite, if there be any, is gradually transformed into sorbite, and disappears altogether at about 150°. Martensite, too, decomposes at a comparatively low temperature and gives sorbite. Its transformation is complete at 300° (Fig. 45). Troostite and sorbite remain unchanged until over 300°, and then they are transformed into cementite and ferrite, separated or united in the euthectic. This means that tempered steel, heated to 300°, loses much of its hardness. Moreover, even when it is completely transformed into the constituents of normal steel, its grain remains very fine and compact. It is therefore usual, in order to give steel this fineness of grain and the consequent freedom from brittleness, to temper it and soften it up to about 600°.

At this point the French are in the habit of plunging it once more into water, to limit the development of cementite and ferrite crystals, and they call this process double tempering.

All steel used for cutlery, surgical instruments, razors, penknives, arms and watch springs, is softened.

These articles, of more or less fine steel, i.e. sometimes of ordinary and often of crucible steel, are first tempered ; then, to make them less brittle, they are

heated to between 220° and 320°, according to the degree of hardness and brittleness which it is desired to leave the pieces, and they are allowed to cool.
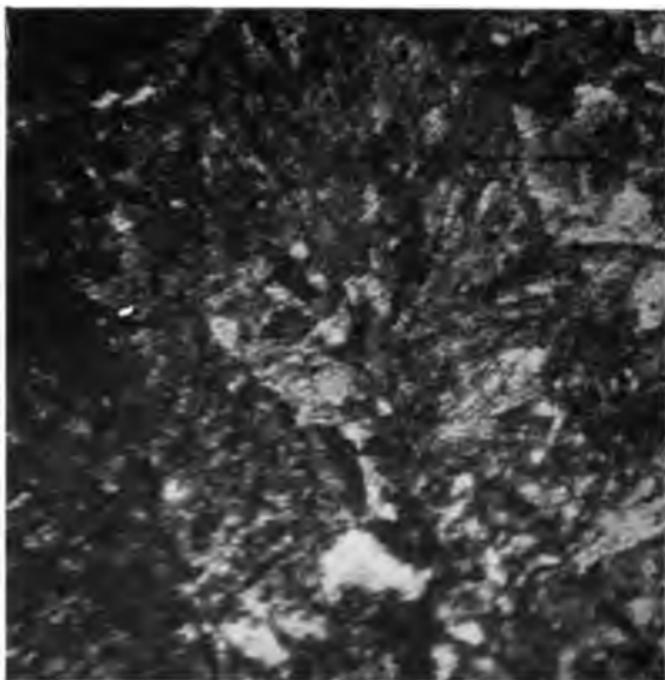

FIG. 45.—Extra hard steel softened at 300°, sorbite and remains of martensite in the centre. Magnified 300 diameters. Acted upon by 5 per cent. picric acid in ethylic alcohol.

Thus they remain formed for the most part of ferrite and sorbite, which are fairly hard, and they keep a very fine grain.

As is well known, during these slight heatings a

thin coating of oxide, which gives a colour varying with the temperature, is formed on the smooth surface of the steel. These colours have from time immemorial served to regulate the heating.

Thus surgical instruments are heated to the so-called pale yellow, which corresponds to about 220°, razors and penknives to dark yellow (240°), scissors to purple (260°), swords to light blue (290°), and saws to dark blue (315°). Metallographic examination now affords scientific means of checking this empirical practice.

Cemented Steel.—This is steel kept for several days at a high temperature (over 860°) in a carburetting medium, such as charcoal powder, lampblack, cyanides or animal residues.

The carbon is dissolved in iron, and if the operation is sufficiently prolonged, the solution gradually makes its way to the interior of the piece. On cooling the carbon takes the form of carbide, as in ordinary non-tempered steel.

Cemented steel is never homogeneous, as it is always much more carburetted near the surface. At one time this system of carburetting was used to turn iron into steel. Now superficial cementation is usually resorted to, i.e. the duration of the heating is limited so as only to let the solution of carbon penetrate a few millimetres below the surface.

If the piece was of soft metal its internal mass remains unchanged, and it acquires a crust rich in

carbon, and therefore very hard. If the cemented piece is subjected to tempering, the mass does not take it, being too poor in carbon, while the outer stratum takes it very strongly, and the difference is intensified. Thus a piece is obtained that can resist shocks, as it has a nucleus of soft material, and at the same time stands superficial wear well, owing to the hardness of the external stratum. These are the properties generally required for toothed-wheels, tools and similar pieces, which are therefore prepared as described.

Cementite, as its name implies, is a metallographic component characteristic of cementation. It is found in all cemented steel, and in the whole area influenced by exterior carburetting action. Its quantity is naturally greatest at the surface and lessens towards the centre.

Cementation is, perhaps, the most delicate and most complex operation in metallurgy. The depth of cementation, i.e. the thickness of the carburetted stratum, and the intensity of carburetting in this stratum, must be checked when the operation is over.

In order to measure the depth of cementation, which is usually prescribed by the consumer, a transverse section of the piece, acted upon by the usual reagents, is placed on the stage of the microscope, so that the outer edge of the specimen corresponds with the limit of the visible field. Then the stage is moved by the use of the fine adjustment until an area of the sample having no trace of cementite is also brought

to the limit of the field. The distance marked by the vernier of the fine adjustment is obviously the depth of cementation. The intensity of carburetting is evident to an expert eye from the quantity of cementite present.
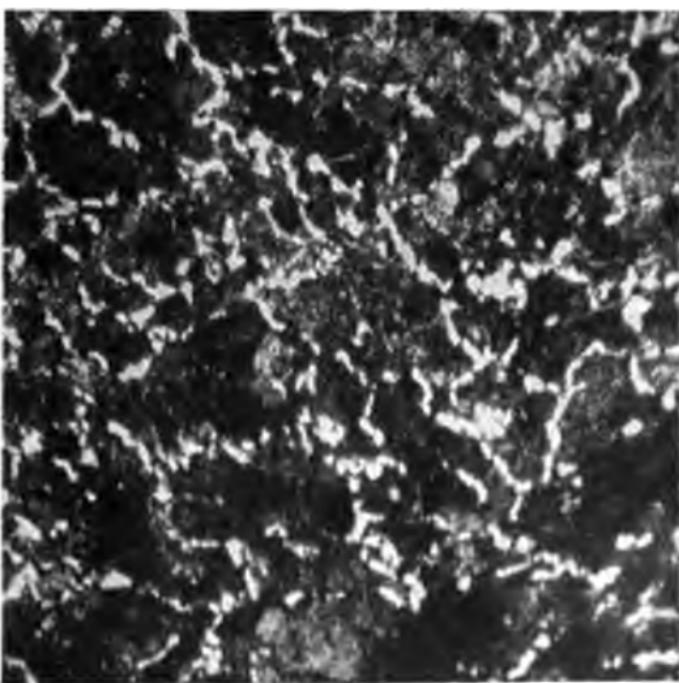

FIG. 46. —Cemented Steel with 0·6 per cent. carbon. Magnified 150 diameters. Photograph taken near the periphery of the sample. Acted upon by Kourbatoff's reagent.

It was the great usefulness of micrographic checks in cementation that first enabled metallographic methods really to triumph in the workshops.

In the great French metallurgic establishments the workmen engaged in cementation put a bar of the same metal as the piece to be treated into the cementing box, so that the two go through exactly the same
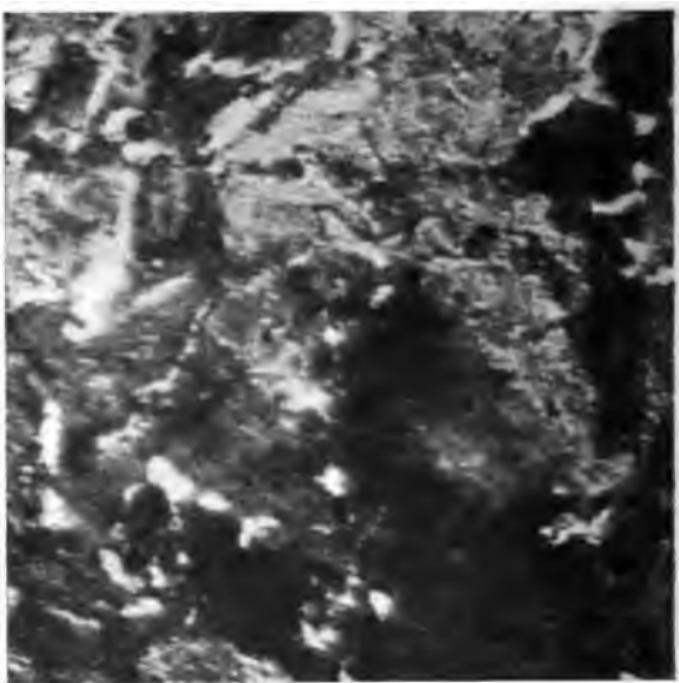

FIG. 47.—The same cemented steel as in Fig. 46. Magnified 650 diameters. Photograph taken near the edge of the carburetted zone.

process ; and in the case of small pieces they put a bar into each box containing a group. When the operation is finished they cut it across and take it to

the *polisseur*, as the workman is called who prepares the samples.

The bar is then taken with the polished piece to the metallographer, who exposes it to chemical action,
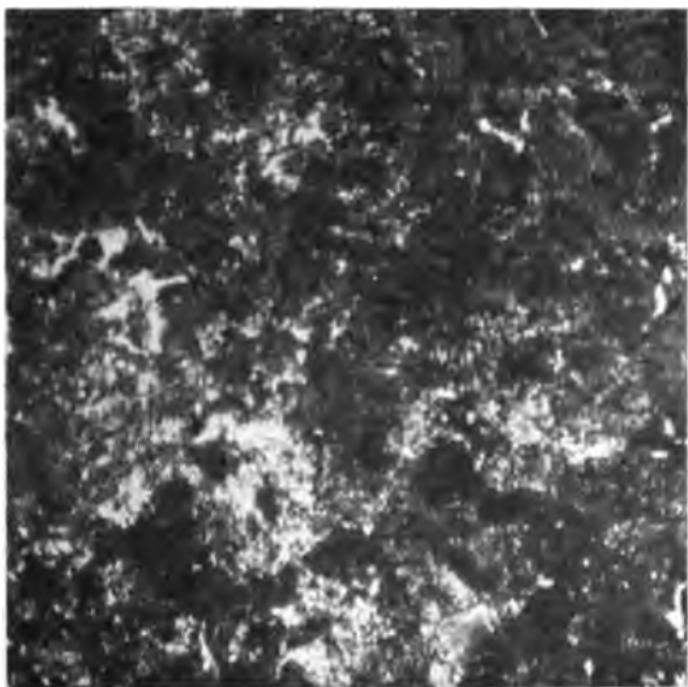

FIG. 48.—Cemented Steel with 0·6 per cent. carbon. Magnified 150 diameters. Photograph taken in the middle of the sample.

examines it under the microscope, and gives his opinion. The piece corresponding with this sample is not allowed to leave the cementing workshop without his sanction.

We give three photographs of the same hard steel submitted to cementation.

The first is taken close to the periphery : it shows a pearlite ground with an abundant network of cementite (Fig. 46).

The second, more highly magnified, is taken near the edge of the carburetted area.   The rapid diminution of the cementite may be observed throughout the photograph (Fig. 47).

The third, beyond the area of cementation, shows the ordinary structure of hard steel, in which pearlite and ferrite are mixed (Fig. 48).

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CHAPTER XI.

TERNARY STEEL.

Nickel Steel.—This is ternary steel, containing, besides iron, variable quantities of carbon and nickel.

This element, like carbon, has the property of lowering the points of the allotropic transformation of iron, but in a more marked degree.

The presence of nickel, indeed, can actually bring down the degrees of thermal change below freezing-point, giving steel in such cases, even without any tempering whatever, the morphological structure which iron does not normally possess except at a high temperature.

Nickel, moreover, does not form special compounds within steel, but gives mixtures isomorphous with iron. Hence such steel has the same constituents as ordinary carbon steel, though different laws affect their distribution.

Cast Nickel Steel is therefore :—

I. *Pearlitic Steel*, in which the change-points are all above the ordinary temperature, as the nickel has not attained to a certain proportion, and the structure, as in carbon steel, is made up of pearlite and ferrite. This keeps the nickel in solution.

This kind of nickel steel is the most commonly used for practical purposes. It is always more homogeneous than the binary, and has a higher resistance when the proportion of carbon is equal. Its resistance to shock (the opposite of brittleness) is much greater.

Such steel, moreover, admits of considerable elongation, so that it can be subjected to a large amount of deformation, which ordinary steel would not stand without breaking. On this account it is much used in practice for pieces exposed to severe shocks, such as certain parts of motor-cars, and for materials which must be hard to split, like plates for ships and artillery material, to take well-known instances.

II. *Martensitic Steel*, in which, owing to a certain proportion of nickel, the change-point A falls below the ordinary temperature. It naturally has the same structure as that kept back by tempering in binary steel, and is wholly constituted by martensite. It is very hard, brittle, and exceedingly difficult to work. Steel which is martensitic throughout has no practical value.

III. *Polyhedric Steel.*—As the percentage of nickel increases, the degrees of thermal change all pass below freezing-point, and the steel presents the structure proper to iron at the highest temperatures, viz. austenite or γ iron, which appears in large polyhedra.

Such steel is very soft; it resists well and admits of very great elongation.

Its characteristic is the almost entire absence of brittleness, and it is consequently valuable for certain special purposes, in spite of its high price and the difficulty of elaboration. This is due to the nature of the chips given off by it, which stick tenaciously to tools, and interfere with the action of the machines elaborating it.

Invar, a polyhedric steel containing 36 per cent. of nickel, possesses the interesting property that its coefficient of dilatation by heat is practically nil. This renders it extremely useful for any apparatus involving precision, such as geodetic instruments, checking scales, or the standards of central offices of weights and measures.

The coefficient of dilatation, which decreases with the rise in the proportion of nickel, until it reaches a minimum at 36 per cent., increases again beyond this percentage. At 46 per cent. it is about equal to that of glass, and steel containing this proportion of nickel is employed instead of platinum, with which the carbon filaments were hitherto attached to the glass, for small incandescent electric lamps. Hence this steel is called *platinite*. Platinite and invar, like all steels rich in nickel, are almost unalterable by atmospheric agents. It has already been observed, with regard to the heating and cooling change-points, that the former are always a few degrees higher than the latter, owing to a phenomenon of hysteresis. Now this becomes very pronounced in nickel steel, growing with the propor-

I

tion of nickel, so that it nearly amounts to 500° C., when the ratio reaches 25 per cent.

The change-points governing the properties of steel at an ordinary temperature are naturally, as a rule, those of cooling, but it must be remarked that steel with high hysteresis may have certain properties, or their opposites, at the same temperature, according to the cycle of temperatures previously passed through. The chief importance of this property is connected with the magnetic phenomena peculiar to the change-points. Steel possessing it is called *irreversible.*

The change-points of nickel steel, though this element has a preponderating influence upon them, also feel that of the percentage in carbon, like binary steel. The two influences therefore sum up, as we shall see from practical examples.

For the two series of photographs shown, certain pieces of nickel steel, kindly given by M. Guillet, were used.

Each of the series shows the influence of the growing percentage of nickel, the proportion of carbon remaining almost constant. If the two be compared, it will be seen that the carbon also contributes to the lowering of the change-points.

Steel Containing 0·25 *per cent. of Carbon.*—Steel containing 2 per cent. of nickel (Fig. 49), has a structure similar to that of carbon steel, but, as may be seen, is finer and more homogeneous. It gave—

$$R = 42.$$
$$A = 21 \cdot 5 \text{ per cent.}$$

Steel with 5 per cent. of nickel (Fig. 50), has a very similar structure, but more minute. The amount of nickel compresses the grains of ferrite.

$$R = 50.$$
$$A = 20 \text{ per cent.}$$

With 7 per cent. of nickel, ferrite and pearlite are still seen, but they are distributed in a special manner,
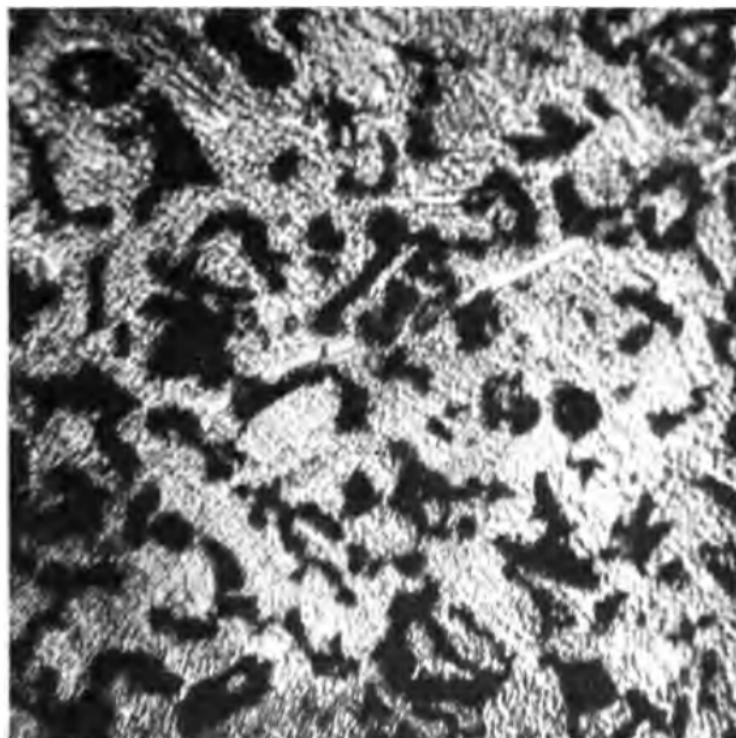

Fig. 49.—Steel with 0·25 per cent. carbon, 2 per cent. nickel. Magnified 650 diameters. Acted upon by 5 per cent. picric acid in ethylic alcohol.

as if disturbed by the approach of a transformation. A tendency to orientate in a peculiar way is also noticeable in the elements.

$$R = 58.$$
$$A = 19 \cdot 5 \text{ per cent.}$$
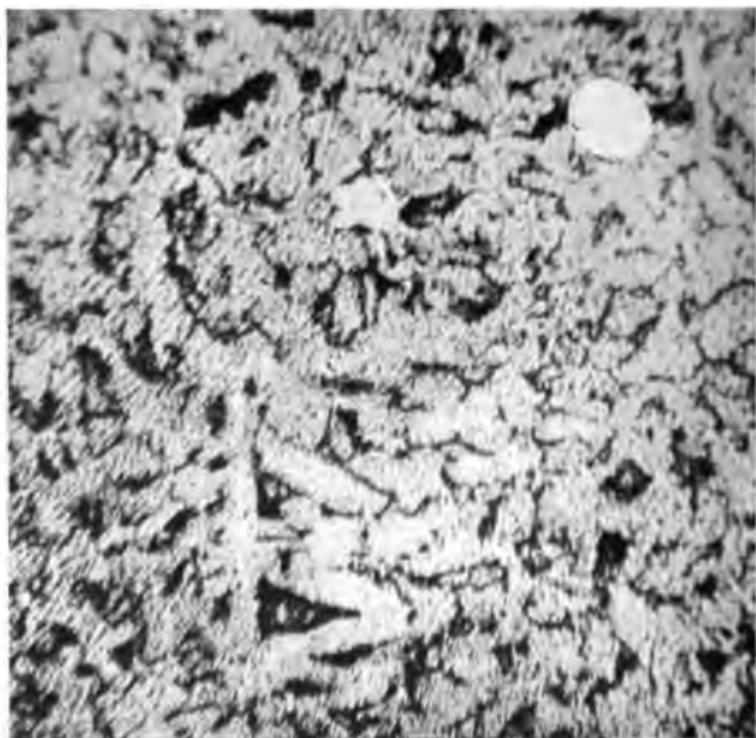
FIG. 50.—C = 0·25 per cent. Ni = 5 per cent. Magnified 650 diameters. Acted upon by 5 per cent. picric acid.

These three types of pearlitic steel, as has been said, have, as a common characteristic, very little

brittleness, or in other words, a great resistance to shock. This resistance, it may be incidentally mentioned, is measured by Frémont's ram, which gives the
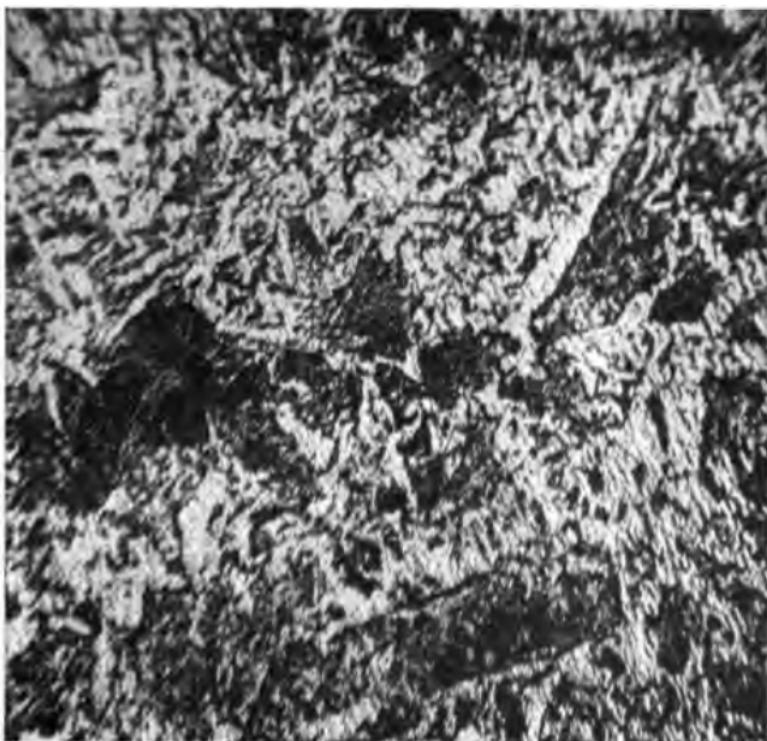

FIG. 51.—C = 0·25 per cent. Ni = 7 per cent. Magnified 650 diameters. Acted upon by 5 per cent. picric acid.

number of kilogrammes (viz. the power) necessary to break by shock a typical sample of the metal examined. This typical sample is 70 mm. square for the breakage

brought about in the required direction, and the split always takes place at a given point.

For the sake of clearness, the results of the experi-
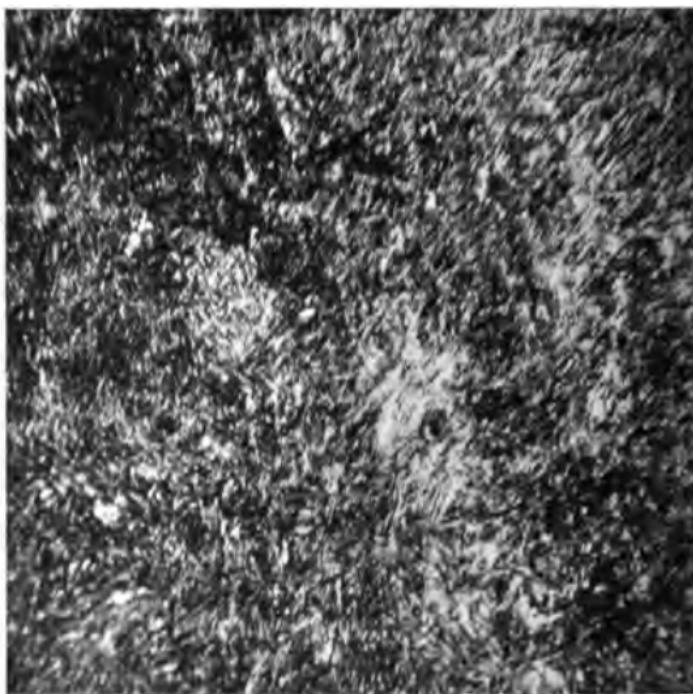
FIG. 52.—C = 0·25 per cent. Ni = 10 per cent. Magnified 650 diameters. Acted upon by 5 per cent. picric acid.

ments made with these typical samples, i.e. the numbers registered by the machine itself, will be given.

This resistance, which, on the average, is 12 kilo. for binary steel with 0·25 carbon, is 20, 18 and 17,

respectively, for pearlitic nickel steel with 2 per cent., 5 per cent., and 7 per cent. of nickel.

It will be seen from the figures given that nickel
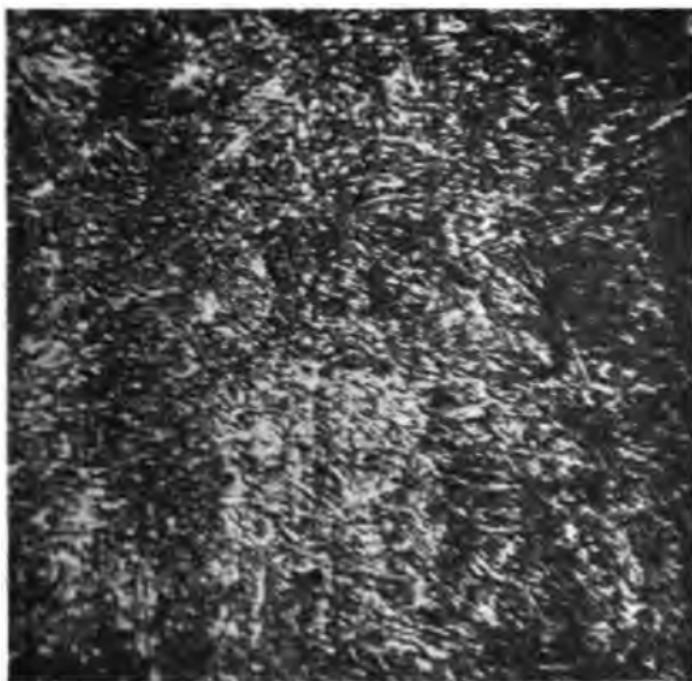
FIG. 53.—C = 0·25 per cent.   Ni = 12 per cent.   Magnified 650 diameters.   Acted upon by 5 per cent. picric acid.

acts like carbon in this first group, raising R, lowering A, and increasing brittleness.

Steel with 0·25 per cent. carbon and 10 per cent. nickel consists wholly of martensite (Fig. 52).

Thus we see a sudden interval in the physical properties. We shall call resistance to shock U.

$$R = 105.$$
$$A = 3 \text{ per cent.}$$
$$U = 3.$$

At 12 per cent. of nickel, martensite, with well-developed elements, continues to hold the whole field (Fig. 53).
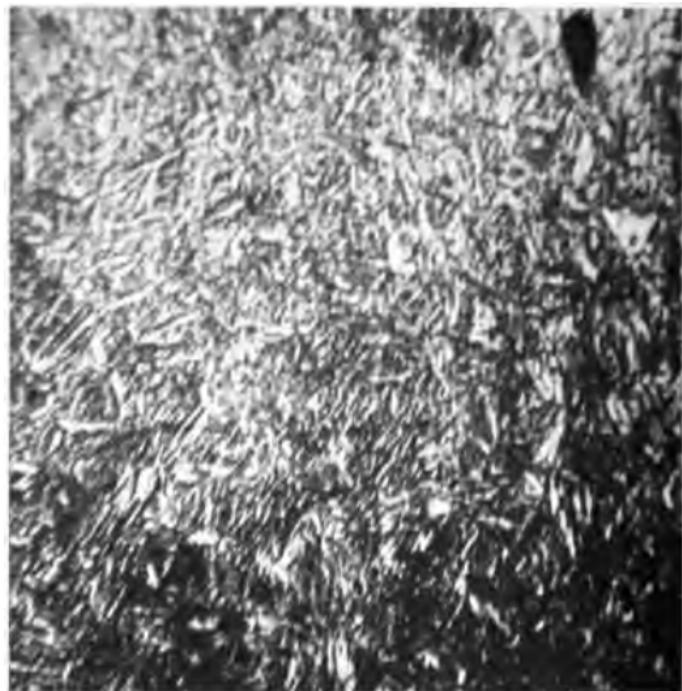

FIG. 54.—C = 0·25 per cent. Ni = 15 per cent. Magnified 650 diameters. Acted upon by 5 per cent. picric acid.

$$R = 125.$$
$$A = 4 \text{ per cent.}$$
$$U = 5\cdot5.$$
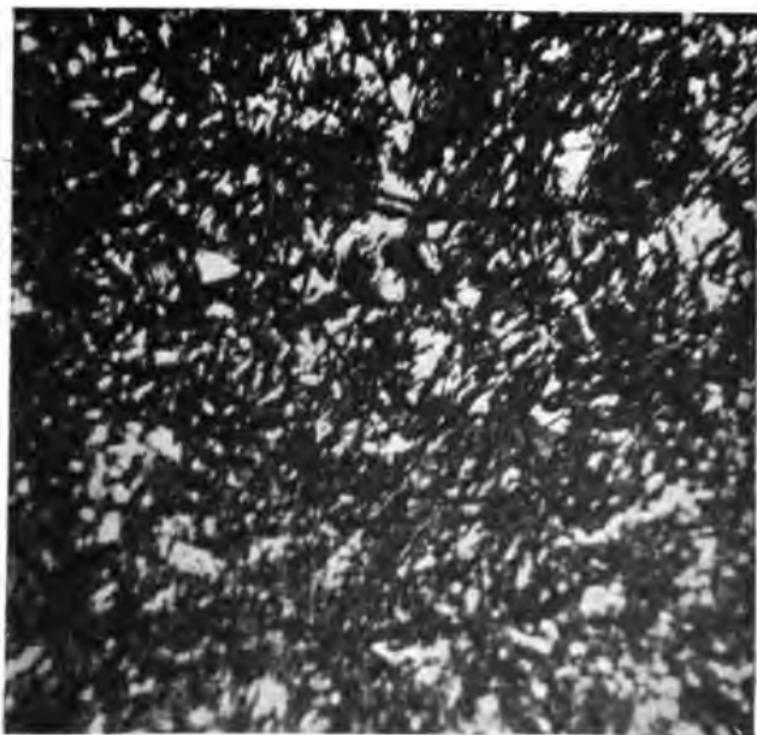
FIG. 55.—C = 0·25 per cent.   Ni = 20 per cent.   Magnified 650 diameters.   Acted upon by 5 per cent. picric acid.

Such martensitic steel possesses exceptional brittleness and hardness (the hardness is proportional to the resistance to strain).

At 15 per cent. of nickel, intensely white elements

appear amidst the martensite (Fig. 54). These are
γ iron, or austenite, which appears and influences the

FIG. 56.—C = 0·25 per cent. Ni = 25 per cent. Magnified
650 diameters. Acted upon by 5 per cent. picric acid.

physical properties, though not as yet to any great
extent.

$$R = 118.$$
$$A = 5 \text{ per cent.}$$
$$U = 7\cdot5.$$

At 20 per cent. of nickel, γ iron abounds, and freely takes its polyhedric form (Fig. 55).

$$R \quad 116.$$
$$A = 5 \text{ per cent.}$$
$$U = 7 \cdot 5.$$

At 25 per cent. of nickel (Fig. 56), the whole sample

FIG. 57.—Steel with 0·8 per cent. carbon, and 2 per cent. nickel.   Magnified 650 diameters.   Acted upon by 5 per cent. picric acid.

is occupied by γ iron in large polyhedra, which give their name to steel with a large percentage of nickel.
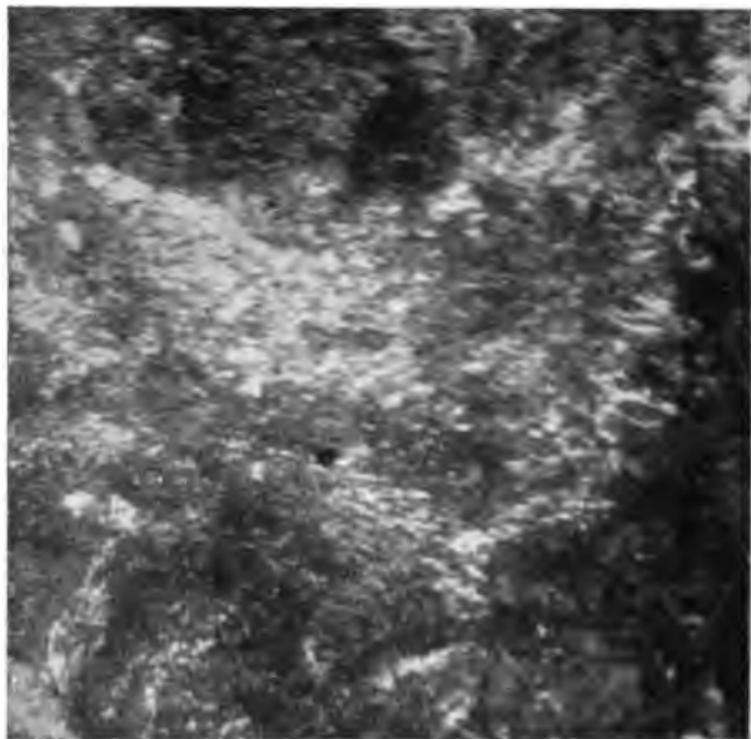

FIG. 58.—C = 0·8 per cent. Ni = 5 per cent. Magnified 650 diameters. Acted upon by 5 per cent. picric acid.

Here the mechanical properties are entirely due to γ iron and its characteristics.

$$R = 55.$$
$$A = 31 \text{ per cent.}$$
$$U = 36.$$

Steel Containing 0·8 per cent. of Carbon.—Steel with 2 per cent. of nickel (Fig. 57) is naturally pearlitic.

$$R = 85.$$
$$A = 16 \text{ per cent.}$$
$$U = 3.$$
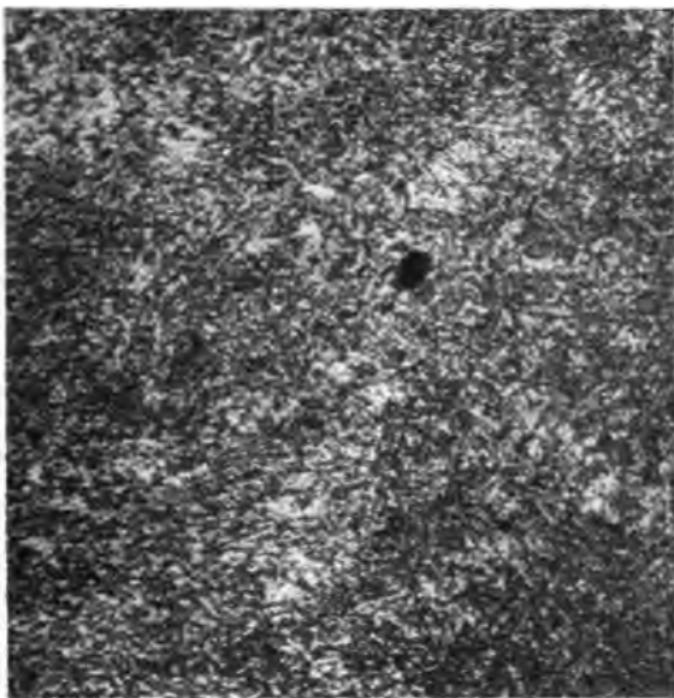
Fig. 59.—C = 0·8 per cent. Ni = 7 per cent. Magnified 650 diameters. Acted upon by 5 per cent. picric acid.

We at once notice a remarkable difference in steel still having 2 per cent. of nickel, but 0·25 per cent. of

carbon, the hardness and brittleness due to the latter being conspicuous. At 5 per cent. of nickel there are some signs of orientation (Fig. 58).
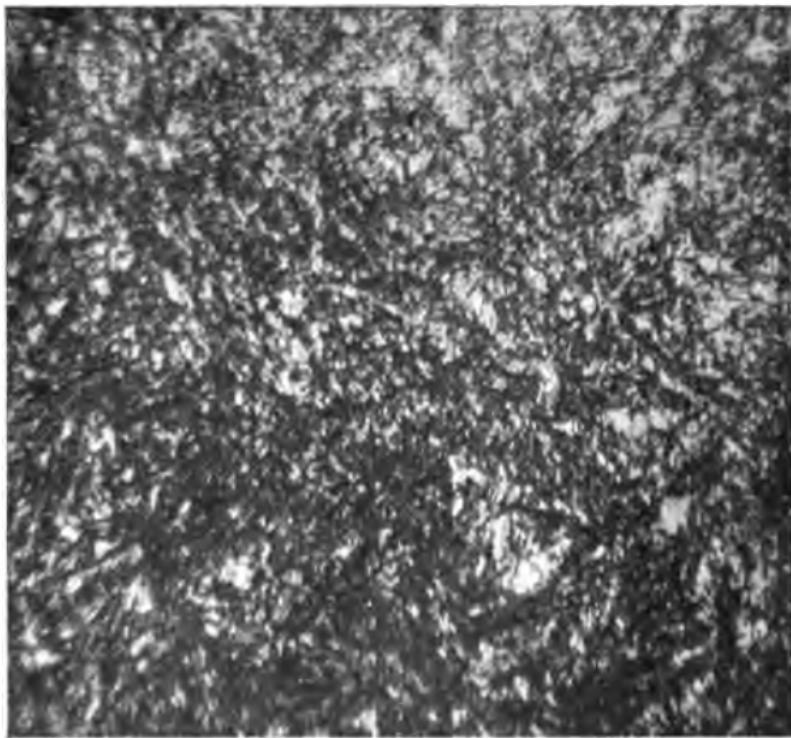

FIG. 60.—C = 0·8 per cent. Ni = 10 per cent. Magnified 650 diameters. Acted upon by 10 per cent. picric acid.

At 7 per cent. of nickel (Fig. 59), the specimen is already composed of very marked martensite. This steel gives hardly any elongation.

R = 114.
A = 0 per cent.
U = 3.

At 10 per cent. of nickel (Fig. 60), the first traces of γ iron appear, considerably earlier than in the other series, in which they only appeared at 15 per cent. We get here :—

R = 104.
A = 3·5 per cent.
U = 3.

At 12 per cent. of nickel γ iron is already very plentiful (Fig. 61), though it still follows, to a slight extent, the disposition of martensite.

At 15 per cent. of nickel it is arranged in its own characteristic way (Fig. 62), and lastly, in steel with 25 per cent. of nickel (Fig. 63), it develops into magnificent polyhedra.

The last gave :—

R = 72.
A = 28 per cent.
U = > 40.

This steel may be said to be practically free from brittleness. It is therefore used for motor-car valves, which are subject to frequent and violent shocks.

The comparison of the two series just shown proves that preponderating action by nickel does not destroy that of carbon, and that the latter, on the contrary, is very marked, so much so that it notably hastens the

change of structure, when the proportion of nickel is the same.

In other words, the proportion of nickel necessary

Fig. 61.—C = 0·8 per cent.　Ni = 12 per cent.　Magnified 650 diameters.　Acted upon by 5 per cent. picric acid.

to give a change of structure decreases with the dimi-nution of the proportion of carbon.

Guillet, after a number of experiments, succeeded in constructing a diagram, on the same plan as that of Roozeboom reproduced by us, making the per-


FIG. 62.—C = 0·8 per cent. Ni = 15 per cent. Magnified 650 diameters. Acted upon by 5 per cent. picric acid.

centages of carbon the abscissæ, and the percentages of nickel the ordinates. The parts into which the area of the diagram is divided show the pearlitic,

K

martensitic or polyhedric structure of the steel corresponding to each pair of values.   On the other hand,

FIG. 63.—C = 0·8 per cent. Ni = 25 per cent. Magnified 650 diameters.   Acted upon by 5 per cent. picric acid.

when the structure of a nickel steel has been examined under the microscope and one of the two percentages is known, the other is discovered at once.   This very

frequently happens in practice, and obviates a chemical analysis.

The *temper* of nickel steel has no practical importance, except in the case of pearlitic steel, which behaves like carbon steel, turning into martensite.

The analogy between the function of nickel and that of carbon is here confirmed, for the presence of nickel causes tempering to be strongly taken by steel which, owing to its small proportion of carbon (less than 0·2 per cent.), would not otherwise take it.

This is shown by the two photographs reproduced (Figs. 64 and 65). The appearance of the untempered steel simply proves its small percentage of carbon.

It may be remarked incidentally that martensitic steel, when tempered, softens, because γ iron, which is soft, is found in it. There appear to be some traces of troosto-sorbite.

The *annealing* of pearlitic steel produces exactly the same effects as in carbon steel.

Martensitic and polyhedric steel, when annealed, produce very complicated phenomena, not yet thoroughly examined and explained. They are not, moreover, of any practical importance.

In the same manner *hammer-hardening* does not cause special phenomena except in polyhedric steel, which becomes magnetic, showing the formation of α iron, in consequence of a raising of the change-points. From the micrographic point of view the formation of

arrow heads of troosto-sorbite is noticed between the polyhedra.

Cementation of nickel steel gives interesting results of great practical importance.
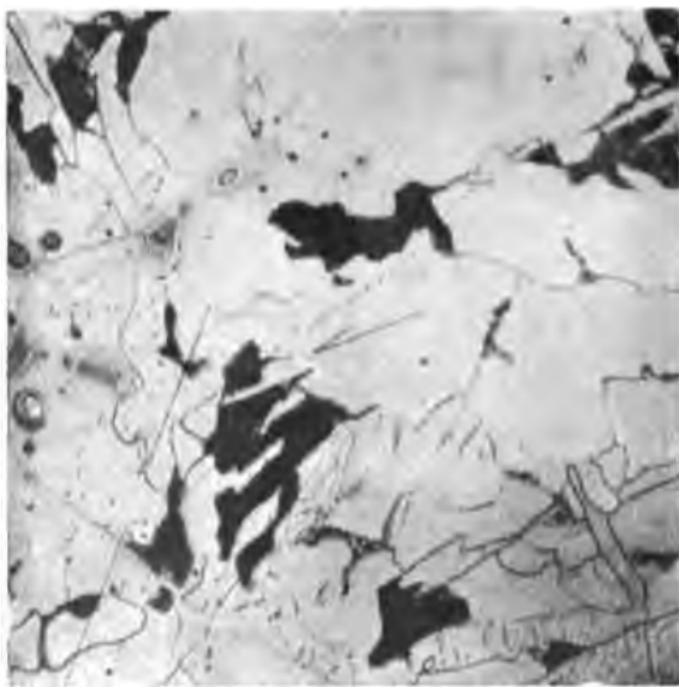

FIG. 64.—Crude Nickel Steel. C = 0·165 per cent. Ni = 1·8 per cent. Magnified 300 diameters. Acted upon by 5 per cent. picric acid.

It has been seen, during the comparison of the two series containing different proportions of carbon, that although the percentage of nickel was the same,

the structure turned from pearlitic to martensitic as the carbon increased. Take, for instance, the characteristic case of steel with 7 per cent. of nickel, which is pearlitic with 0·25 per cent. of carbon and martensitic with
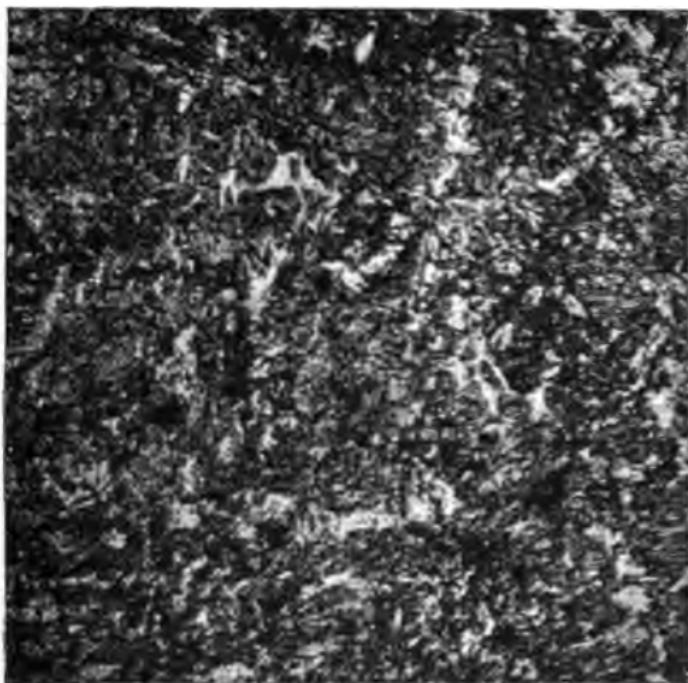

FIG. 65.—The same steel as in Fig. 64, tempered at 800° C. in water. Magnified 300 diameters. Acted upon by 5 per cent. picric acid.

0·8 per cent. The consequence is, that if pearlitic steel is subjected to cementation, the outer stratum, growing rich in carbon, becomes martensitic.

Thus cementation alone produces the same effect as requires cementation, followed by tempering, in carbon steel.

Martensitic steel, when cemented, gives γ iron at its periphery, and this may happen in the martensitic stratum just mentioned, if cementation is prolonged too much.

Polyhedric steel does not change appreciably.

Nickel steel is by far the most important kind of ternary steel; the others have a much less conspicuous place in practical connections.

Manganese Steel.—Manganese is found in all steel, and there is rarely less than 0·2 per cent. of it. In fact, it is present in iron minerals, and then, under various forms, it is added to molten steel, to reduce the oxide of iron dissolved in it, which would make the steel brittle. The manganese oxidises and passes into the slag, in quantities equal to the reduced iron, and the surplus remains in the metal. The manganese also appropriates and carries off into the slag any sulphur that may happen to be in the steel. Sometimes little cubes of sulphide of manganese remain in the latter.

It is only when the proportion of manganese exceeds 1 per cent. that the product is commonly called *manganese steel.*

Manganese influences steel, with regard to the change-points and the varieties of structure, in the same way as nickel, and what has been said of the one

applies to the other. It only remains to be added that, with a very high percentage of carbon, martensitic steel shows cementite (as it is usually called, though it contains manganese as well as iron), or, to speak more correctly, double carbide of manganese and iron. Martensitic and polyhedric steel are not well adapted for such treatment as tempering, annealing and cementation. Pearlite steel behaves exactly like carbon steel.

Chrome Steel.—Chrome in steel has the characteristic function of opposing both the disintegration and the reconstitution of cementite; it therefore raises the point A c in heating, and lowers the point A r in cooling.

First comes pearlitic, and then martensitic steel, depending simultaneously upon the percentage of chrome and of carbon. Beyond a certain percentage intensely white· grains of double carbide of chrome and iron form within the martensite, and gradually end by occupying the whole field. Chrome steel presents a very great resistance to strain by extension and to pressure.

The effect of elaboration on such steel is much the same as in the preceding cases. When tempered it gives an exceptionally fine grain. Steel containing nothing but chrome has greatly lost its practical value.

Tungstic and *molybdenic steel* have properties similar to those of chrome steel as regards the change-points. They furnish pearlitic and double carbide steel. Martensite can be obtained in them by tempering, if they

are pearlitic, or by heating them to 1000° C. and letting them cool in the air, if they have a double carbide. This forming of martensite constitutes a real tempering, and the phenomenon is therefore called tempering by air, of which we will treat at greater length in connection with quaternary steel. When cemented, tungstic and molybdenic steel are enriched by double carbide, and when annealed they soften.

Vanadium steel is similar to the two last mentioned, but possesses the peculiarity of containing pearlite and double carbide together at certain percentages, and of having carbide alone when the proportion of vanadium is very great. Temper acts on the pearlitic part alone. Annealing softens and, in highly carburetted steel, eliminates graphite. Hammer-hardening gives great brittleness; cementation increases the carbon.

Silicon steel has the character, confined to itself, of being independent in its structure of the percentage of carbon. This is the opposite of what happens in the steels previously described.

Metallurgical chemistry shows that silicon tends to precipitate carbon in the form of graphite. Micrographic examination shows the presence of graphite with 5 per cent. of silicon; at 7 per cent. the whole of the carbon assumes this form. A small percentage of silicon forms silicide, FeSi, which dissolves in ferrite. With a medium percentage another silicide, Fe_2Si, appears. With 25 per cent. a composite, $FeSi_2$, is formed.

Tempering and cementation are only possible in steel free from graphite, the quantity of which is increased by annealing.

All metals and several metalloids have been combined with iron and carbon to give special kinds of ternary steel. It is unnecessary to enter into details concerning them, as they are merely curiosities of the laboratory, devoid of practical utility. Moreover, their properties are similar to one or other of those described.

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CHAPTER XII.

QUATERNARY STEEL.

THIS is steel containing iron, carbon and two other elements.

Chromo-Nickel Steel.—Its structure is the resultant of the above-described influences of nickel and chromium. These influences either act simultaneously, or one prevails over the other, according to the proportion of each element. Thus pearlitic, martensitic (Fig. 66) and carbide steel, polyhedric steel, or steel that is polyhedric and carbide at once, are obtained.

The mechanical properties feel the effects of similar influences.

Such steel is much used, because the combination of these influences can be combined so as to give them both great hardness and little brittleness.

Chromo-Tungstic or High-Speed Steel.—This contains, in the types now generally adopted, o·625 per cent. of chromium, up to 18 per cent. of tungsten and at times also 5 per cent. of vanadium, added to reduce and absorb the gases evolved during fusion.

Such steel is called high-speed, because it can be

used for cutting tools working at very high speeds, sufficient to make them red-hot, without their softening and losing the required hardness, as ordinarily tempered steel would.
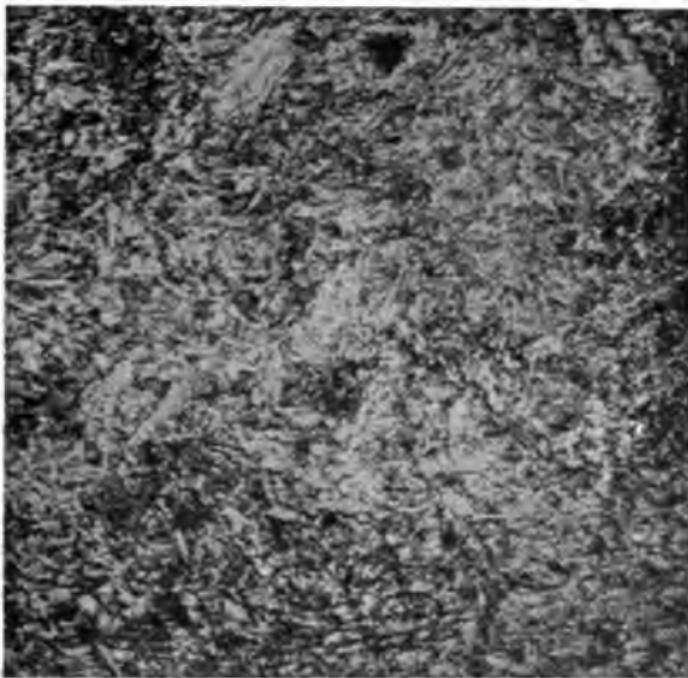

FIG. 66.—Chromo-nickel Steel. C = 0·277 per cent. Cr = 7 per cent. Ni = 4·1 per cent. Magnified 300 diameters. Acted upon by aqua regia.

As it contains a large percentage of tungsten, it has double carbide, and can therefore be tempered by simply heating it almost to melting-point

and letting it cool in the air. Hence it is called *self-hardening*.

These strange phenomena are explained, if it be
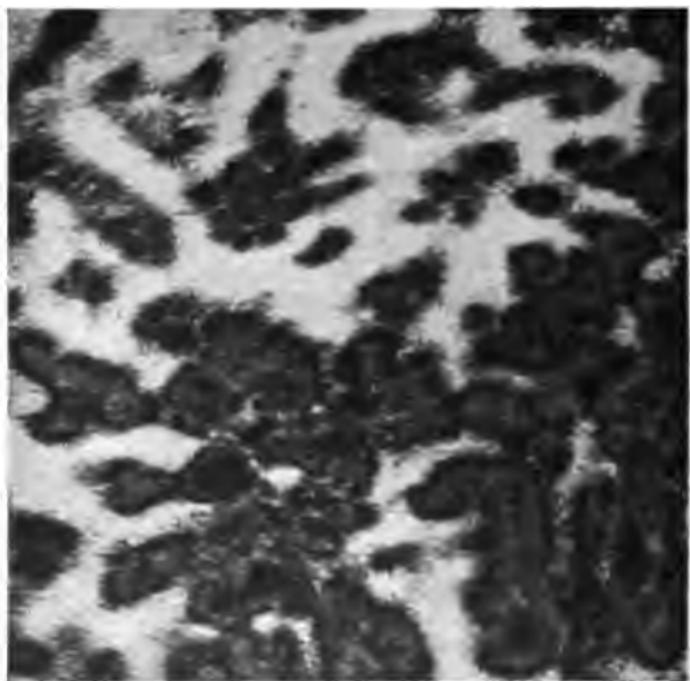
F IG. 67.—High-speed Steel. C = 0·35 per cent. Cr = 4·6 per cent. W = 18·2 per cent. V = 0·4 per cent. Magnified 300 diameters. Acted upon by aqua regia.

recognised that chromium and tungsten hinder the formation of cementite, i.e. the conversion of carbon from dissolved into combined, so that steel, once heated, even when it cools slowly , preserves the constitution of

high temperatures, remaining, as it were, tempered. On the other hand, even when made red-hot, it remains hard, unlike other steel, which softens through the
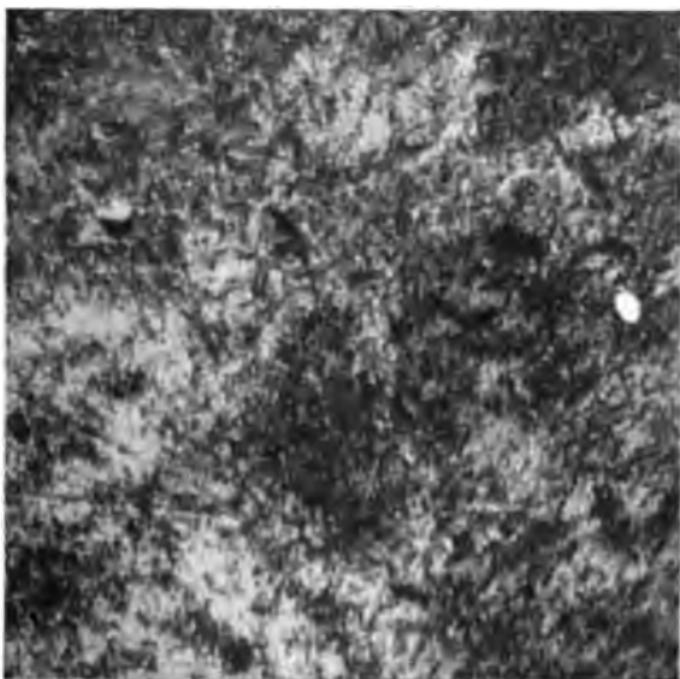

FIG. 68.—High-speed Steel. C = 0·58 per cent. W = 10·2 per cent. Cr = 8·3 per cent. Magnified 300 diameters. Acted upon by aqua regia.

formation of cementite, as this cannot be formed in high-speed steel.

This steel now occupies a prominent place in metallurgy, owing to the great saving in time, and

therefore in labour, which it brings about, allowing machine tools, e.g. lathes, to work five or six times faster than ordinary tools. Thanks to it a given establishment can perform work that at one time would have required five times as much plant.

Unfortunately, its micrographic examination has hitherto borne but little fruit, as it has been impossible to ascertain the exact relation between its micrographic appearance (Figs. 67 and 68), and the mechanical properties it should possess.

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CHAPTER XIII.

CAST-IRON.

CAST-IRON is defined : the siderurgic products obtained by treating iron ore in blast furnaces. The name is also given to metal obtained by a second casting of these products, and employed in castings without further treatment.

It is less easy to define cast-iron from the point of view of its composition and structure, since it resembles steel in too many particulars, without a clear boundary line between the two. Still, the practical definition given above is sufficient to distinguish it.

The great bulk of ordinary cast-iron contains 3 per cent. of carbon, and a sum of about 7 per cent. of elements other than iron, i.e. carbon, silicon, manganese, sulphur and phosphorus.

Carbon is found in the combined state, as in carbon steel in the graphite state, or as in ternary silicon steel. According as one or the other condition of carbon prevails, cast-iron is called white or grey. There is also a cast-iron intermediary between white and grey, which is called mottled iron.

White Cast-Iron.—This contains the whole of the

carbon in the combined state.   Under the microscope
it is seen to be made up of pearlite and free cementite
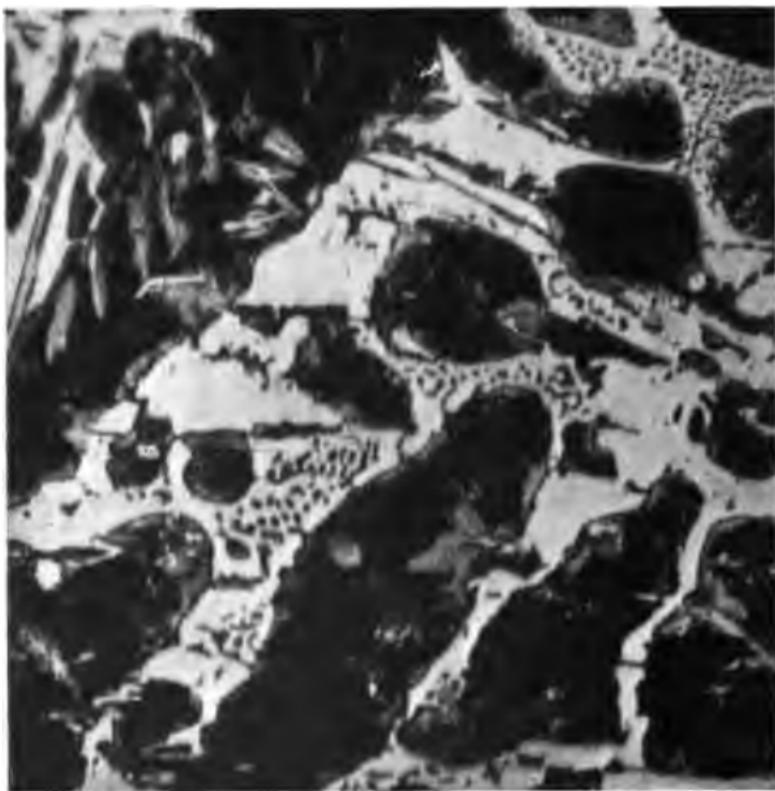

FIG. 69.—White Cast-iron.   Acted upon by Kourbatoff's
reagent.

(Fig. 69).   The quantity of the latter increases with
the percentage of carbon.

    Cast-iron chiefly becomes white through the influ-

ence of manganese, which, as has been known for a long time, keeps carbon in the combined state, entering into the composition of cementite. The same result is obtained, when there is little manganese, by quickly cooling cast-iron (as in chill casting), since this prevents the carbide from decomposing.

White cast-iron, being composed of pearlite and cementite (Fig. 70), has metallographically the same composition as extra hard steel, which contains more than 0·85 per cent. of carbon. Hence a scientific definition of white cast-iron, based upon its structure, is impossible.

A compound of pearlite and cementite containing over 2 per cent. of carbon is called cast-iron; one containing less is called steel. This distinction is evidently quite arbitrary and conventional. When, for instance, the proportion of the bath in the Bessemer converter reaches 2 per cent., it is impossible logically to say whether the metal is at the moment steel or cast-iron.

As the amount of carbon in cementite (6·67 per cent.) and in pearlite (0·85 per cent.) are known, metallographic examination gives a fairly exact idea of the proportion of carbon in white cast-iron.

Owing to its high percentage of cementite, white cast-iron is very hard, cannot be wrought and is exceedingly brittle. By means of chill casting it is formed on the surface of pieces which must be outwardly very hard in order to wear well.

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Spiegel-iron, or specular-iron, which is introduced into molten iron to deoxidise and recarburet it, is a white cast-iron, very rich in manganese, of which it
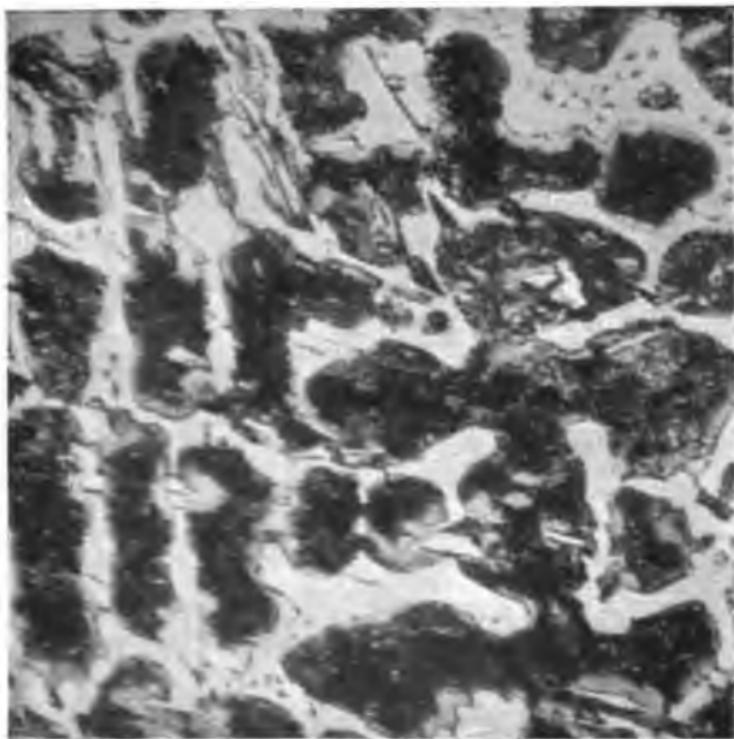

FIG. 70.—White Cast-iron. Magnified 650 diameters. Acted upon by Kourbatoff's reagent.

may contain as much as 25 per cent. Beyond this proportion the alloy of iron, manganese and carbon is called *manganese-cast-iron*, and can also be classed with these products.

Grey Cast-Iron.—This has already been said to be cast-iron containing the whole of the carbon in the state of cast-iron. This definition is really unpractical and too narrow, since almost all grey cast-iron has part of its carbon combined. It may be better described as cast-iron composed of ferrite, pearlite and graphite, and devoid of free cementite.

Grey cast-iron is always chemically characterised by a considerable quantity of silicon (1·5–3 per cent.).

It is this which precipitates the carbon as graphite, much as was seen to happen in silicon steel. Grey cast-iron resembles this from the structural point of view, as white cast-iron does extra hard carbon steel.

However, as carbon is very abundant in cast-iron, it begins to separate and crystallise in the melted mass, forming fairly large strips, which remain in the metal when it solidifies.

The metallic part of grey cast-iron would not be very brittle in itself, since it is made up of pearlite and ferrite, but the large strips of graphite that intersect it in all directions (Fig. 71), causing infinite breaks in continuity, detract greatly from the resistance of the metal. We shall return to this subject when speaking of malleable cast-iron.

As it does not contain cementite, grey cast-iron is not hard, and lends itself to being elaborated by machine-tools.

Grey cast-iron often contains considerable quantities of phosphorus, which is seen in the form

of phosphide of iron in intensely white layers
(Fig. 72).

Micrographic examination greatly helps, and in a

FIG. 71.—Grey Cast-iron. Magnified 150 diameters. Acted
upon by Kourbatoff's reagent.

manner peculiar to itself, in giving an idea of the resist-
ance of cast-iron employed in castings.

The judgment is based upon the quantity of graphite

FIG. 72.—Phosphorous Grey Cast-steel. Magnified 150 diameters.
Acted upon by Kourbatoff's reagent.

met with and upon the size of its elements, which, as has been said, are the cause of brittleness.

In foundries it is customary to mix cast-iron from different sources in order to obtain special qualities in the metal, and the microscope reveals the exact results of these mixtures.

In cast-iron intended to be refined for the production of steel, micrographic examination shows, in much less time than chemical analysis, whether there are white layers of phosphide of iron. Phosphorus, as is well known, is indispensable for the processes of basic refining, while it is absolutely inadmissible for acid processes.

When the proportion of silicon in grey cast-iron is over 7·8 per cent., it is called *ferro-silicon.* This special alloy, whose proportion in silicon may be over 60 per cent., is used for the final additions to Bessemer-Martin steel.

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CHAPTER XIV.

MALLEABLE CAST-IRON.

WHEN pieces of white cast-iron are subjected to annealing prolonged for several days above 900°, in sand contained in suitable vessels, these pieces lose a great deal of the hardness and brittleness characteristic of white cast-iron.

The product obtained is called malleable cast-iron. Until recently its formation was generally attributed to the decarburetting of white cast-iron, and it used therefore to be annealed in an oxidising medium, such as powdered oxide of iron mixed with sand, with the object of burning the carbon and thus reversing the process of cementation, or accomplishing a sort of refining without the fusion of the cast-iron.

But micrographic examination showed that, while the outer stratum of pieces thus treated is easily deprived of carbon and reduced almost wholly to ferrite, all the rest of the sample is made up of ferrite, pearlite and much graphite, so that the effective diminution of the quantity of carbon within is very small, and may be compared with that obtained in all annealing processes (Figs. 74 to 80).

On the other hand, chemical analysis shows that the mean percentage of carbon is not so much less, in
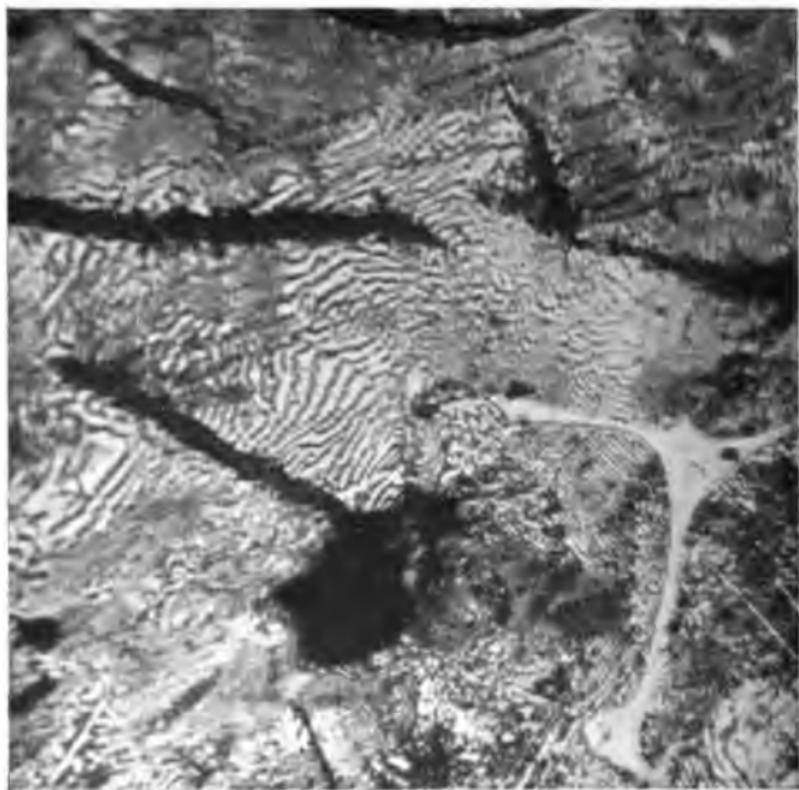

FIG. 73.—Grey Cast-iron. Magnified 650 diameters. Acted upon by 5 per cent. picric acid.

malleable cast-iron than in the white cast-iron which was the starting point, as to produce a profound modification in mechanical properties.

The conversion of white into malleable cast-iron is therefore essentially not a process of decarburetting, but one of annealing, which precipitates a great pro-
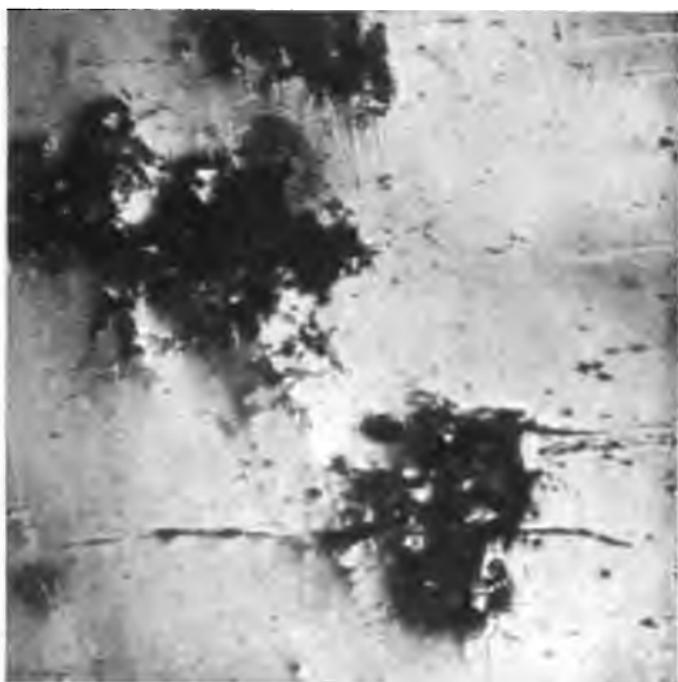

FIG. 74.—Malleable Cast-iron obtained by annealing the white cast-iron in Fig. 70. Outer portion, ferrite and graphite. Magnified 650 diameters.

portion of the combined carbon into the state of graphitic carbon, transforming the metal composed of cementite and pearlite into metal composed of pearlite, ferrite and graphite. But this latter composition is

the same as that of grey cast steel, and it may at first sight seem absurd that, whereas this is brittle, the same elements may be attributed to malleable steel, whose characteristic is absence of brittleness.
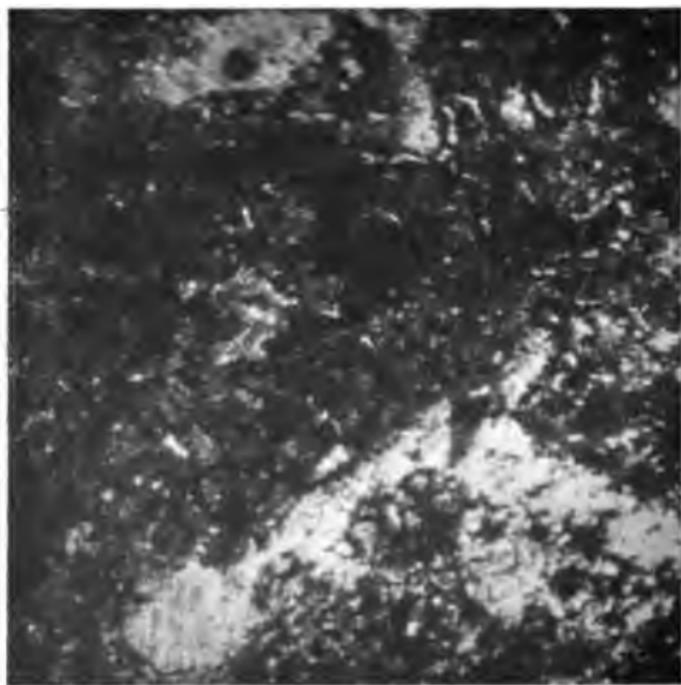

FIG. 75.—The same cast-iron as in Fig. 74. Central portion, pearlite, ferrite and graphite. Magnified 650 diameters.

It is sufficient to examine and contrast the photographs to explain this apparent paradox. In grey cast-iron, as has been said, graphite, having crystallised in the melted mass, forms large layers that intersect

the metal (Fig. 73).   This is made up, as it were, of a number of distinct pieces, joined together by slender isthmuses, and its resistance is therefore very slight.

Instead of this the graphite, in malleable cast-iron,


FIG. 76.—Malleable Cast-iron, obtained by annealing the white cast-iron of Fig. 69.   Outer portion, ferrite and graphite.   Magnified 300 diameters.   Acted upon by 5 per cent. picric acid.

is deposited within the solid mass, during the decomposition of the carbide.   Being compressed by the ferrite and pearlite, it remains undecomposed, and

cannot crystallise, since it continues to be amorphous and subdivided into very small grains (Fig. 74). The metal forms a compact whole, merely permeated by
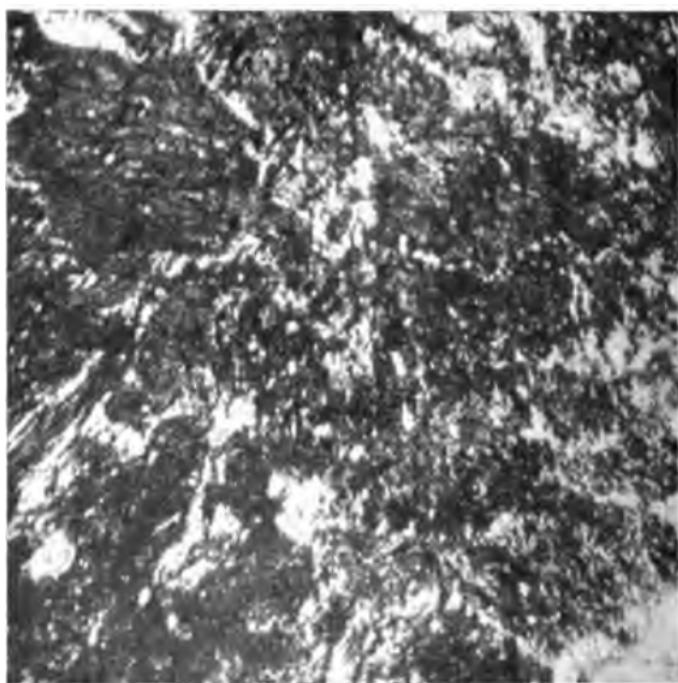

FIG. 77.—The same cast-iron as in Fig. 76. Central portion, pearlite, ferrite and little graphite. Magnified 300 diameters.

little globes of graphite, which cannot greatly affect its resistance.

The practical conclusion to be drawn from these laboratory experiments is the uselessness of adding oxidising substances to the sand in which the pieces
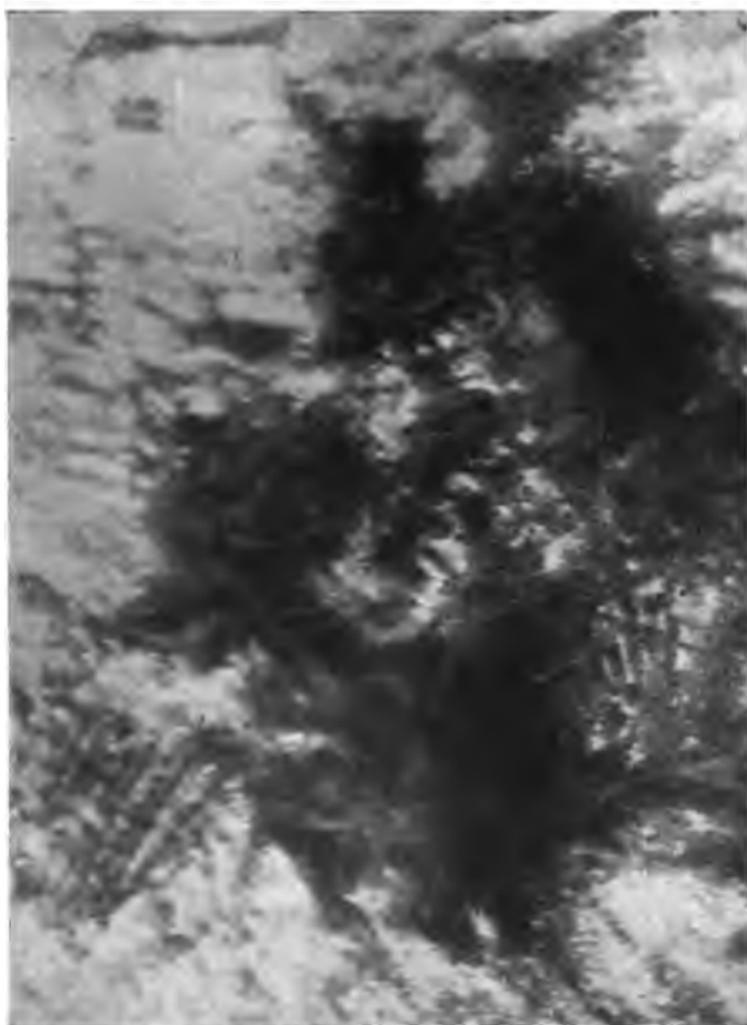
FIG. 78.—The same cast-iron as in Figs. 76 and 77. One grain of graphite highly magnified.

are annealed to convert them into malleable cast-iron, and which serves to reduce the action of air upon the metal. The process is thus simplified and rendered cheaper.
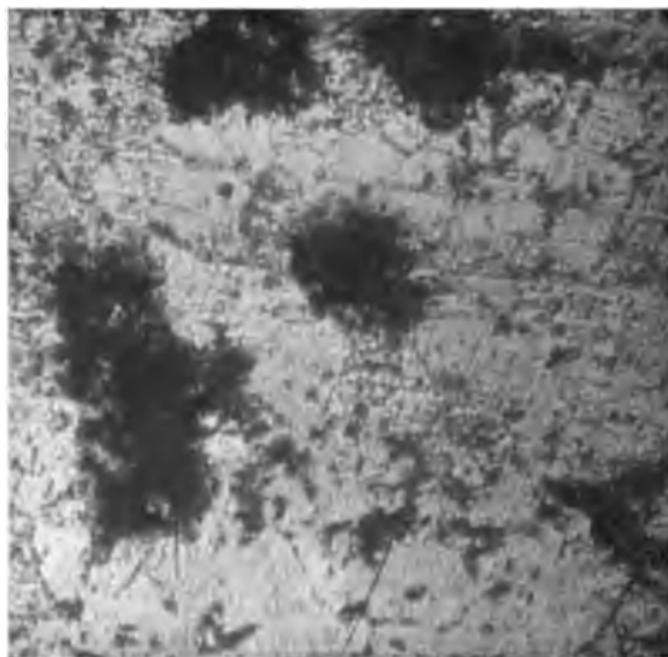

FIG. 79.—Malleable Cast-iron. Outer portion, graphite and ferrite. Magnified 300 diameters. Acted upon by 5 per cent. picric acid.

American metallurgists have all admitted this, and the whole of the workshops in the United States now prepare malleable cast-iron with the aid of plain sand. In Europe the old system has hitherto been adhered to.

With a view to introducing the rational American method in Italy, and to conquer the fear that manufacturers felt of adopting it, we have undertaken a series
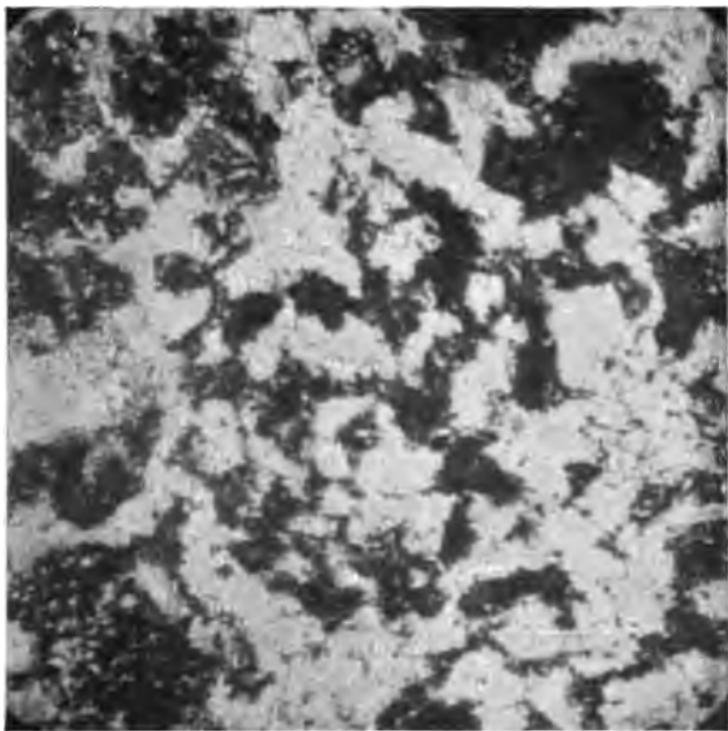

FIG. 80.—The same cast-iron as in Fig. 79.   Intermediate portion, ferrite, graphite and little pearlite.   Magnified 300 diameters.

of experiments capable of showing the practical man the possibility of passing from one system to the other without risk of the manufacture turning out badly.

In the first place, in order to show that the essence of the process of rendering cast-iron malleable, even in an oxidising medium, consisted in precipitating the graphite, we attempted to watch the process of transformation at its inception.

For this purpose a furnace was stopped that had been for 48 hours at the required temperature—whereas the usual number is 96 hours—and thus incompletely annealed pieces were extracted. These pieces, under the microscope, showed the structure given here (Fig. 81). The formation of white cast-iron, with cementite and pearlite, was still almost intact. Amid them were already precipitated grains of graphite, coming from the decomposed, rather than decarburetted, cementite.

If decarburetting were the chief result, the carbon should have disappeared, not reappeared in a different form.

It was, above all, necessary to show that cast-iron annealed in plain sand gave the same results as that annealed in sand and oxide of iron. Judgment could be pronounced exhaustively by comparing the structure of the two and their respective physical properties.

Among the latter resistance to shock was especially to be considered, as it is that required by testers, who, in practice, give violent blows with a hammer to the pieces submitted to them. In the second place strength for extension and the limit of elasticity, upon which the malleable nature of the metal depends, were to be gauged. It is, in fact, the custom to test the

pieces by bending them till they break, and measuring the greatest angle they are able to stand.
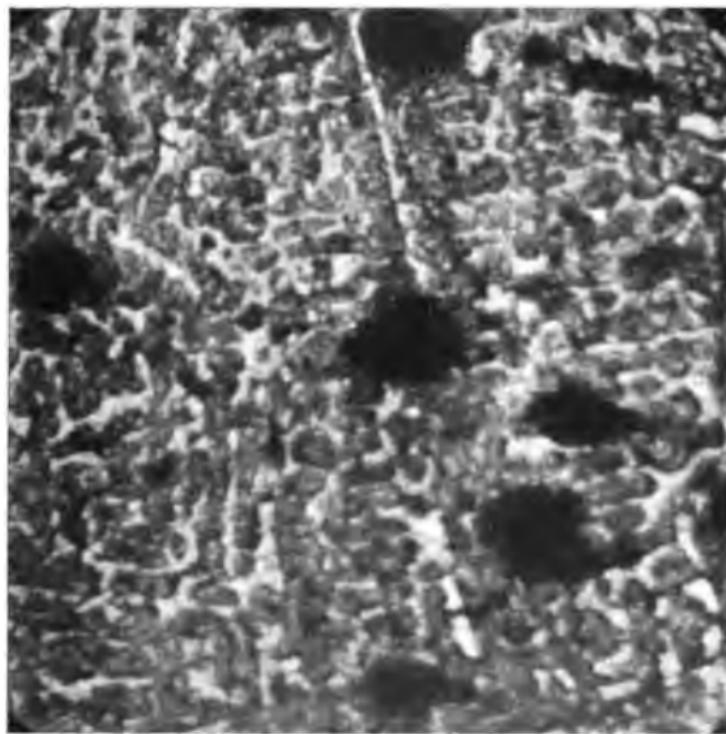

FIG. 81.—An intermediate product between White and Malleable Cast-iron. Cementite, pearlite and graphite. Acted upon by Kourbatoff's reagent.

A few groups of white cast-iron, to be rendered malleable, were chosen. The pieces of each group were identical in composition, shape and the thickness

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of the various parts ; but the pieces of one group differed from those of the others in the same particulars.

Comparisons were then instituted between the eight pieces of which each group was composed.

A box of cast-steel was taken 8 mm. thick and 0·40 × 0·20 × 0·15 cm., divided vertically in two by a partition of the same height as the box, and perfectly separating the two halves.

One of these contained a layer, 4 cm. deep, of the mixture previously used for rendering cast-iron workable, consisting half of sand and half of dried and finely powdered oligoschist.   Upon this layer, at equal distances, were placed 4 pieces belonging to one group, and the half of the box was filled in, up to a centimetre from the top, with the same mixture.

In the other half the remaining four pieces of the same group were laid upon 4 cm. of pure sand, and they were covered with it.

The first half was also filled up with pure sand, to prevent any idea that the oxide might have passed from it to the second.

The box was covered with a strip of steel of the same size and thickness, and was properly closed up with mud made of pounded aluminous brick and of greasy fireclay.

Then the box was put into a cold annealing oven, in such a manner that each part should equally be acted upon by the heat.

The annealing was done in the usual way, heating

the furnace to 950° for the space of 20 hours, keeping it at that temperature for 96 hours, and then letting it cool.

The pieces were then taken out, and were carefully kept apart ; samples for the mechanical tests and for micrographic examination were then taken from each. Thus it became possible to compare the physical and structural qualities of identical pieces, dealt with under the same conditions as to heat and in a different medium.

The experiments were repeated several times in the same manner, and many photographs and numerical data were collected.

The results agreed remarkably.

We give here those obtained with regard to three qualities of cast-iron, i.e. to groups belonging to three different castings.

The letter R shows the resistance to breaking strain by extension, E the limit of elasticity, also by extension, and U the resistance to shock, according to the convention already explained.

The proportion of carbon shown is that in the white cast-iron before annealing.

From these figures, considering the constancy of the general result, definite conclusions may be drawn.

We see that the mean resistance to breaking strain is higher in pure sand, and that, on the other hand, the elastic limit is less in two cases out of three.

This shows that metal annealed in pure sand, besides having greater resistance, can stand greater elonga-

Group	Percentage of carbon	Annealing medium	R		E		U	
			Partial	Mean	Partial	Mean	Partial	Mean
I	2·18	Mixture of sand and oligoschist	24·5		14·1		3·5	
			27·0		15·5		2·8	
			26·2		13·2		3·0	
			25·5	25·8	13·2	14·0	2·7	3·0
		Pure sand	30·9		12·8		4·5	
			29·1		12·2		4·8	
			29·8		14·9		6·2	
			27·8	29·4	14·1	13·5	4·9	5·1
II	2·46	Mixture of sand and oligoschist	30·5		16·2		2·2	
			31·6		17·0		1·6	
			32·3		17·0		1·9	
			31·2	31·4	15·4	16·4	2·7	2·1
		Pure sand	33·3		16·1		2·9	
			32·1		15·8		3·5	
			31·2		14·8		3·0	
			33·1	32·6	15·3	15·5	3·8	3·3
III	2·27	Mixture of sand and oligoschist	24·8		13·1		5·2	
			24·1		13·4		5·3	
			25·4		12·2		5·9	
			24·5	24·7	13·7	13·1	5·6	5·5
		Pure sand	31·6		14·5		6·2	
			32·8		13·9		5·6	
			32·2		13·1		5·3	
			31·4	32·0	13·7	13·8	6·1	5·8

tion before breaking. It is, in other words, more malleable.

But the most remarkable differences are in resist-
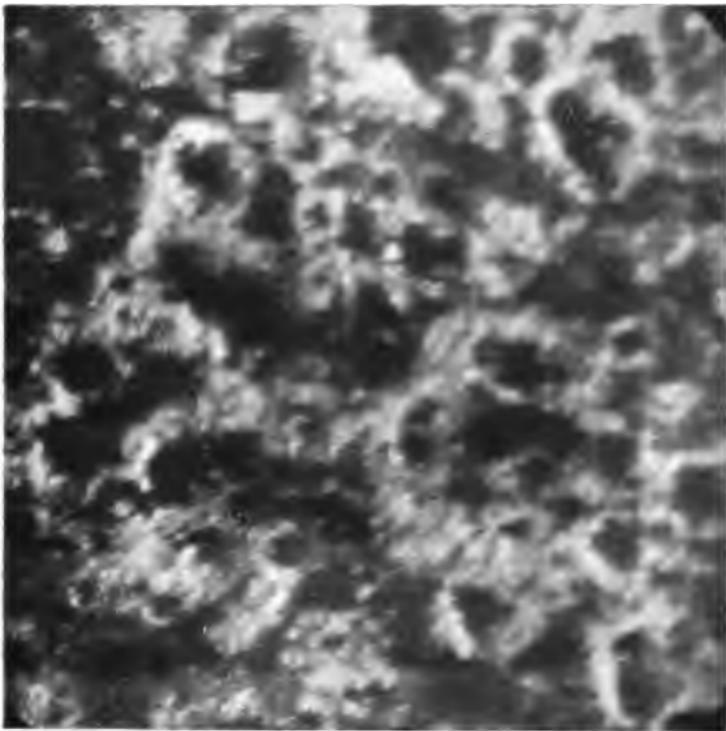
FIG. 82.—Malleable Cast-iron of group I. (see Table), annealed in sand and oligoschist. Magnified 100 diameters. Acted upon by Kourbatoff's reagent.

ance to shock. The advantage on the side of pure sand is constant and, especially in the first two groups, very marked.

From the physical properties it may be concluded
that the two systems give results differing but slightly,
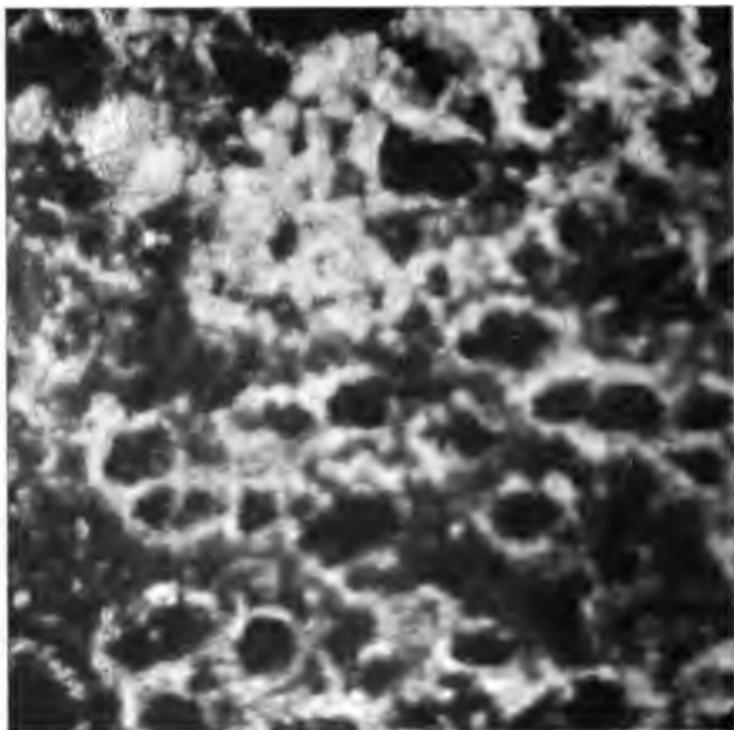
FIG. 83.—Malleable Cast-iron of group I., annealed in pure
   sand.   Magnified 100 diameters.   Acted upon by Kourba-
   toff's reagent.

with a certain advantage in favour of pure sand, which,
moreover, is cheaper.

How can the better results as to elongation and
brittleness, given by sand alone, be explained ration-

ally? We do not hazard any conjectures on this point, as we have no data to go upon. It may perhaps
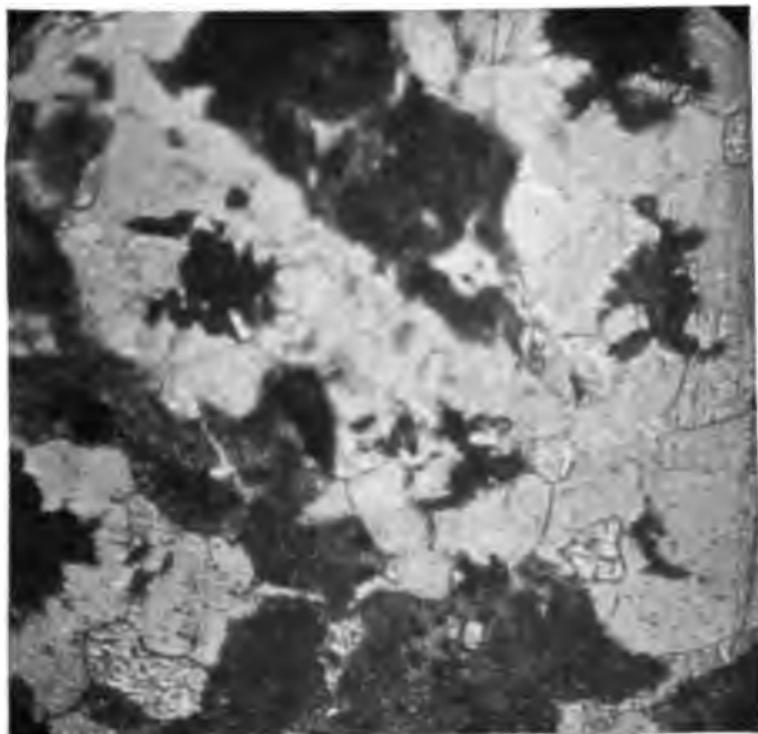
FIG. 84.—Malleable Cast-iron of group I., annealed in sand and oligoschist. Magnified 300 diameters. Acted upon by Kourbatoff's reagent.

be suggested that iron ore, as it always contains large quantities of sulphur, transmits a certain portion of it, through prolonged contact at a high temperature, to

the metal, which thus loses in the capacity for being wrought and in resistance to shock.

Let us now see how metallographic examination
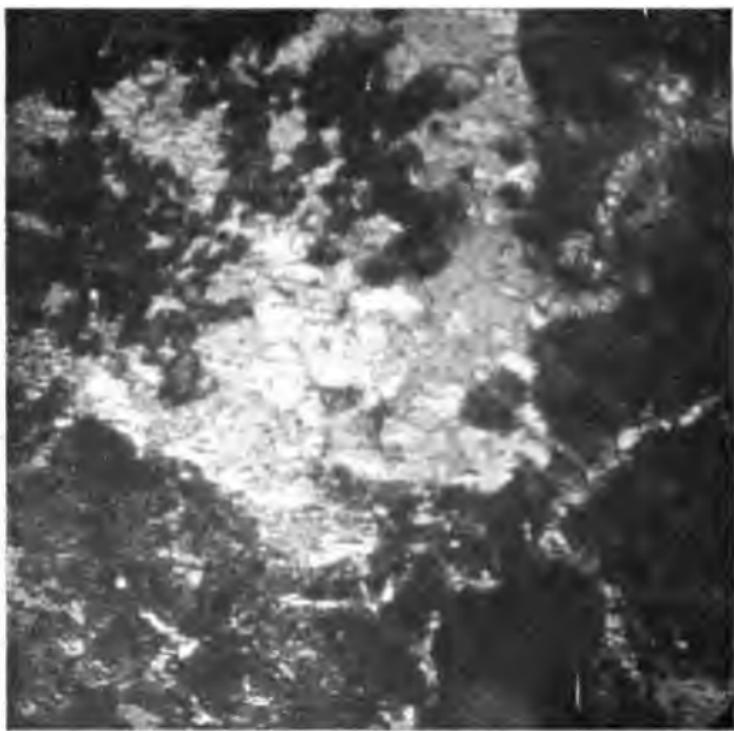
FIG. 85.—Malleable Cast-iron of group I., annealed in sand alone. Magnified 300 diameters. Acted upon by Kourbatoff's reagent.

can inform the metallographer, in similar cases, as well as mechanical tests.

We show a piece annealed in sand and oligoschist,

and one annealed in sand alone, for each of the three groups of cast-iron.

Each has ferrite, pearlite and graphite in almost
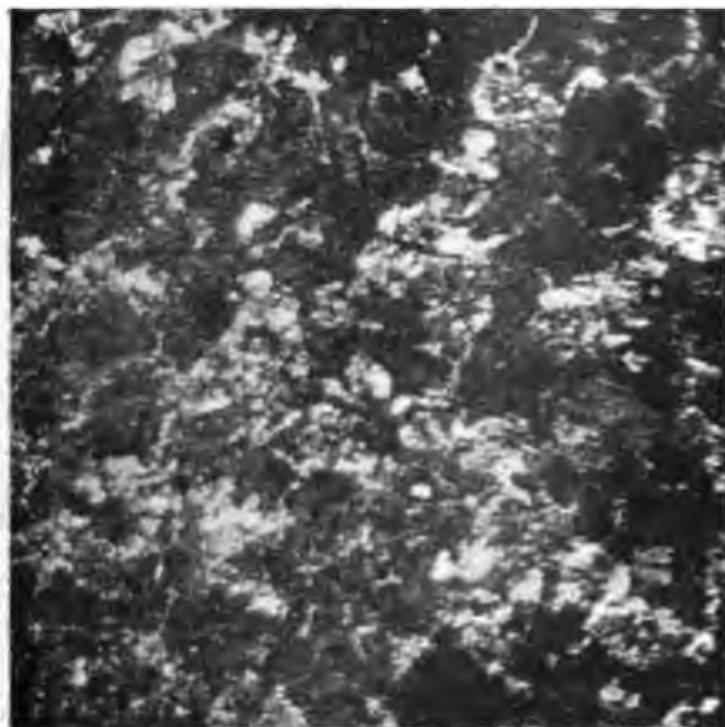
Fig. 86.—Malleable Cast-iron of group II. (see Table), annealed with sand and oligoschist. Magnified 300 diameters. Acted upon by Kourbatoff's reagent.

equal relative proportions: the general structure and grain of the metal are also similar.

· The metallographer, by means of this examination

alone, would be enabled to conclude that the physical properties are equal in the two sets of metals, and that the two methods are equivalent.
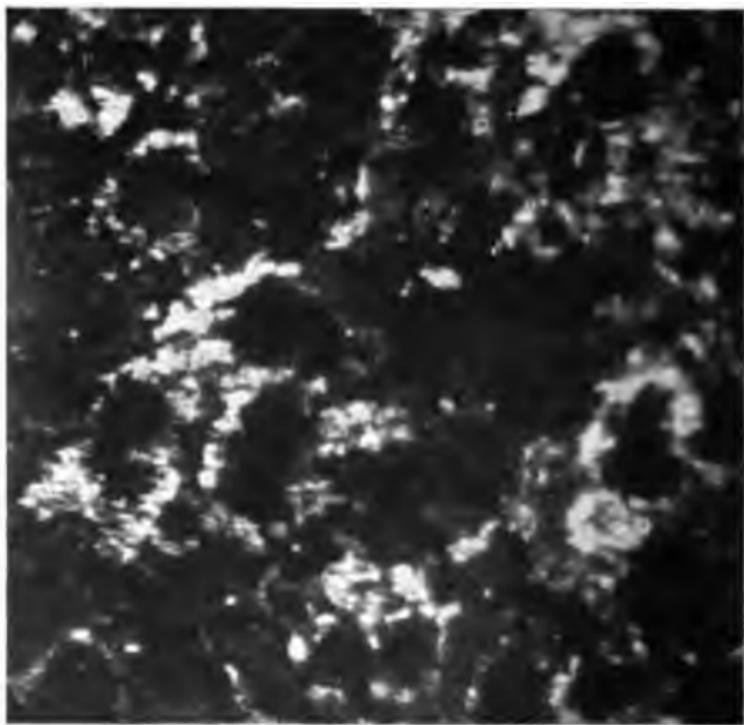

FIG. 87.—Malleable Cast-iron of group II., annealed in pure sand. Magnified 300 diameters. Acted upon by Kourbatoff's reagent.

The double basis of these conclusions has empowered us to advise, on our responsibility, the adoption of annealing in pure sand, all other conditions remaining equal.

For the past year and a half this method has alone been adopted. In this time thousands of tons of material have been delivered and taken into use, with-
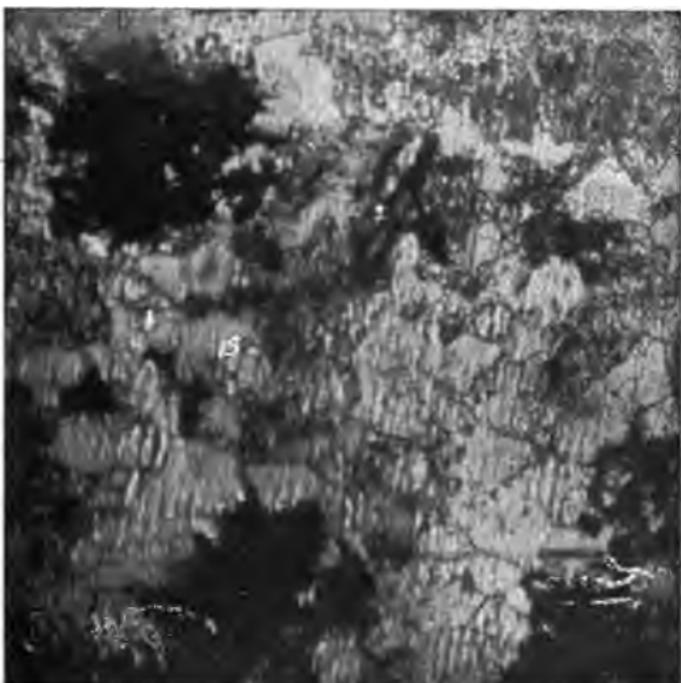

FIG. 88.—Malleable Cast-iron of group III. (see Table), annealed in sand and oligoschist. Magnified 300 diameters. Acted upon by Kourbatoff's reagent.

out the purchasers having made any observations or complaints, and without anyone even having noticed a change in the quality of the metal.

The manufacturer saves the cost of purchase, dry-

ing and grinding of the mineral, besides that of the extra metal which had to be left in the pieces to be annealed, so as to make up for the amount destroyed
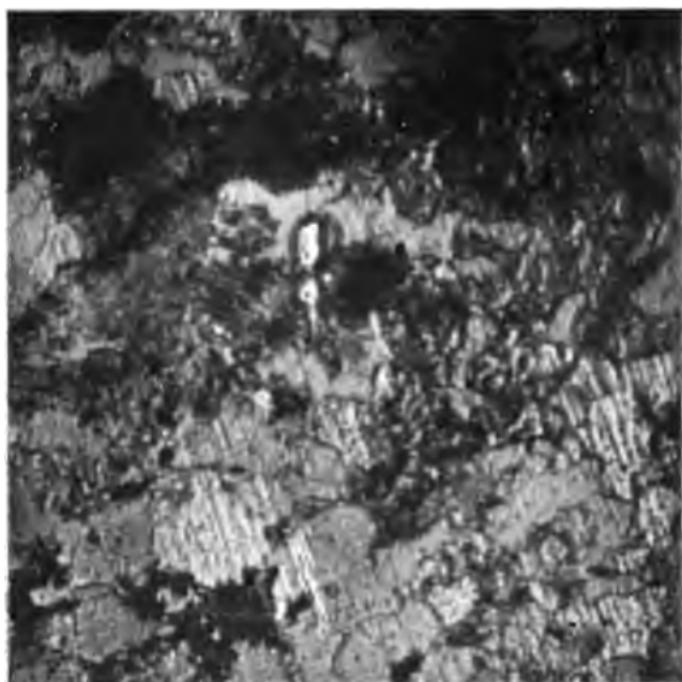

FIG. 89.—Malleable Cast-iron of group III., annealed in pure sand. Magnified 300 diameters. Acted upon by Kourba-toff's reagent.

by the deep oxidising which the oligoschist effected on the surface.

It must be observed that the cast-iron for the pieces to be made malleable can be prepared, in

a cupola furnace, from a suitable mixture of white cast-iron, or by means of the converter, using the usual grey cast-iron intended for the manufacture of steel, and burning off a great proportion of the silicon; which, as is well known, may be eliminated in the first place by the action of the air injected into the converter.

When, by following the operation with the spectroscope, it is seen that the carbon begins to burn, the operation is stopped and the cast-iron, rendered white by the elimination of the silicon, is cast in moulds. A small quantity of silicon may remain without changing the quality of the cast-iron, and, when this is annealed, it facilitates the precipitation of the graphite.

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CHAPTER XV.

IN order to see the different constituents that form in
different degrees of tempering, a small parallelopiped
40 mm. × 10 mm. × 8 mm., and having 0·8 per cent.
of carbon, was taken. It was well polished along its
whole length, 40 mm. × 10 mm.

The piece was heated, care being taken that this
should be done uniformly in every part, and too deep
oxidising was provided against by keeping it immersed
in, and completely surrounded by, a large Bunsen's
flame, hanging it up by means of a thin platinum wire.

As it was desired to find out the practical limits
of tempering, it was only heated to 1000°, a Le
Chatelier platinum and radiated platinum pyrometer
being used to register the temperature. The soldering
of the thermo-electric couple was brought almost in
contact with the piece.

After 15 minutes of heating, it being considered
that the whole mass had the same temperature, the
piece, still held in a vertical position by the platinum
wire, was suddenly plunged into a bath of water at

15°, but only for 10 mm., the other 30 mm. being kept outside the bath.   The piece was then left until it had completely cooled.
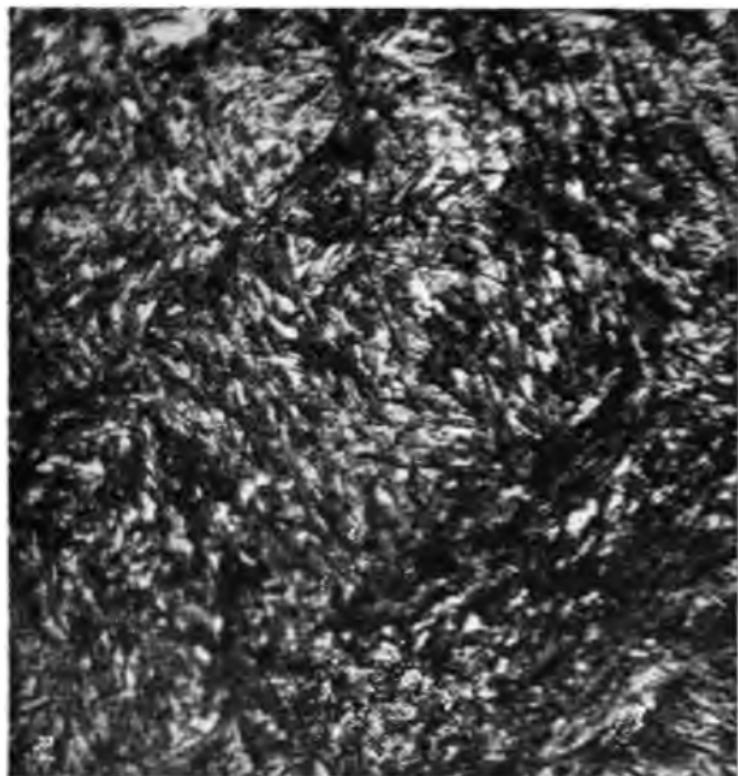

FIG. 90.—Partially tempered Steel.   Martensite.   Magnified 650 diameters.   Acted upon by Kourbatoff's reagent.

The prepared surface was then polished again, to remove the oxide and complete the burnishing ; always, however, under a stream of water, so that there should

be no rise in temperature to alter the results of tempering.   The smooth surface was acted upon by 4 per
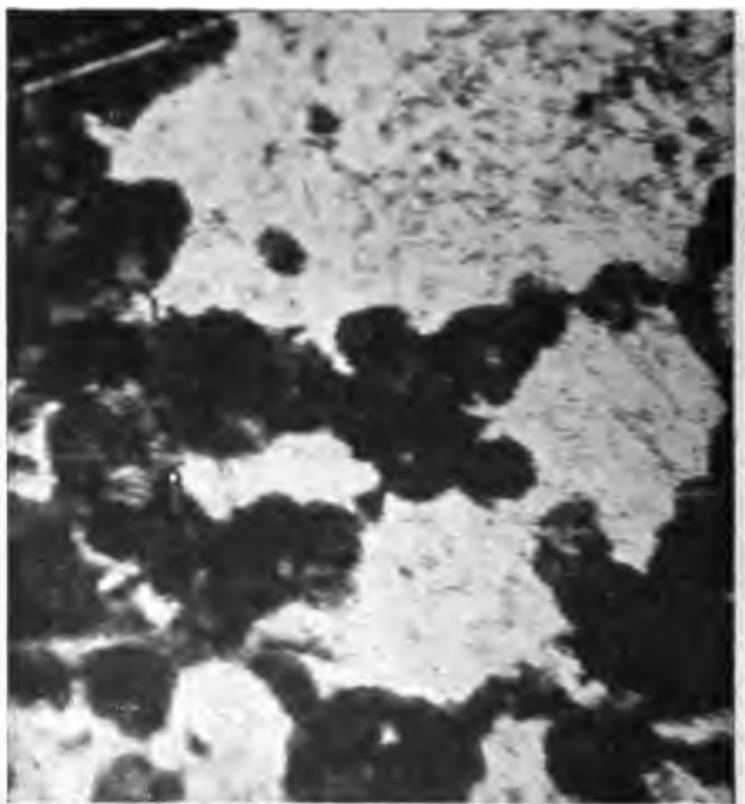
Fig. 91.—Partially tempered Steel.   Martensite and troöstite.
Magnified 650 diameters.   Acted upon by Kourbatoff's reagent.

cent. nitric acid in amylic alcohol, and examined under
the microscope.

The part plunged into water, as was to be foreseen,

FIG. 92.—Partially tempered Steel. Martensite, troostite and sorbite. Magnified 650 diameters. Acted upon by Kourbatoff's reagent.

showed compact martensite, with well-developed crystals, brought into considerable relief by the

FIG. 93.—Partially tempered Steel. Martensite and sorbite. Magnified 650 diameters. Acted upon by Kourbatoff's reagent.

chemical action, as the shadows on the photograph show (Fig. 90).

The same structure continues for 3 mm. above the limit of immersion. The subtraction of heat by con-
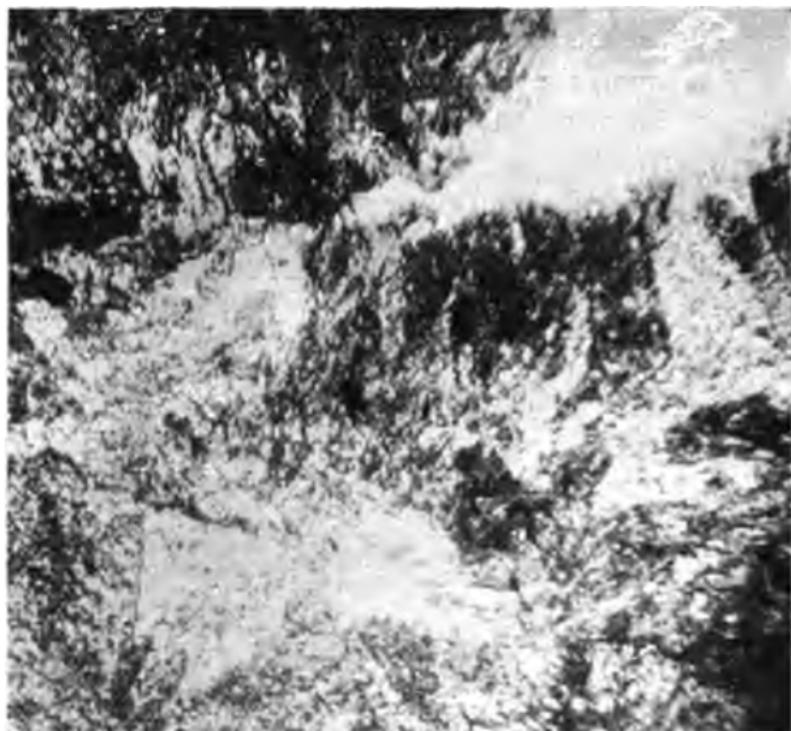
FIG. 94.—Partially tempered Steel.—Martensite, sorbite, little pearlite and ferrite. Magnified 650 diameters. Acted upon by Kourbatoff's reagent.

duction was evidently strong enough to produce complete tempering. The martensite, however, becomes lighter, since the relief of the crystals composing it diminishes.

At 4 mm. from the level of immersion, troostite globules, a characteristic constituent of mild and incomplete tempering, appear (Fig. 91). It will be noticed that the martensite is already much lighter.

At 8 mm. the field of martensite is quite , white. The details in the relief between crystal and crystal disappear, and only rough lines are to be seen. There is still much troostite, and sorbite appears. This is especially distinct in the lighter nucleus, between the two troostite nuclei, in the mass of martensite (Fig. 92).

At 10 mm. there is great prevalence of martensite and sorbite. Only a few traces of troostite are met with (Fig. 93).

Finally, at 12 mm., while the last layer of martensite lies on one side of the field, reduced to a white spot almost without relief, we see the sorbite in contact with it, then come the pearlite and even a few small spots of ferrite, as far as this is compatible with the high percentage of carbon in the steel (Fig. 94).

From this point upwards, the steel remains pearlitic, and has not been influenced by the process gone through.
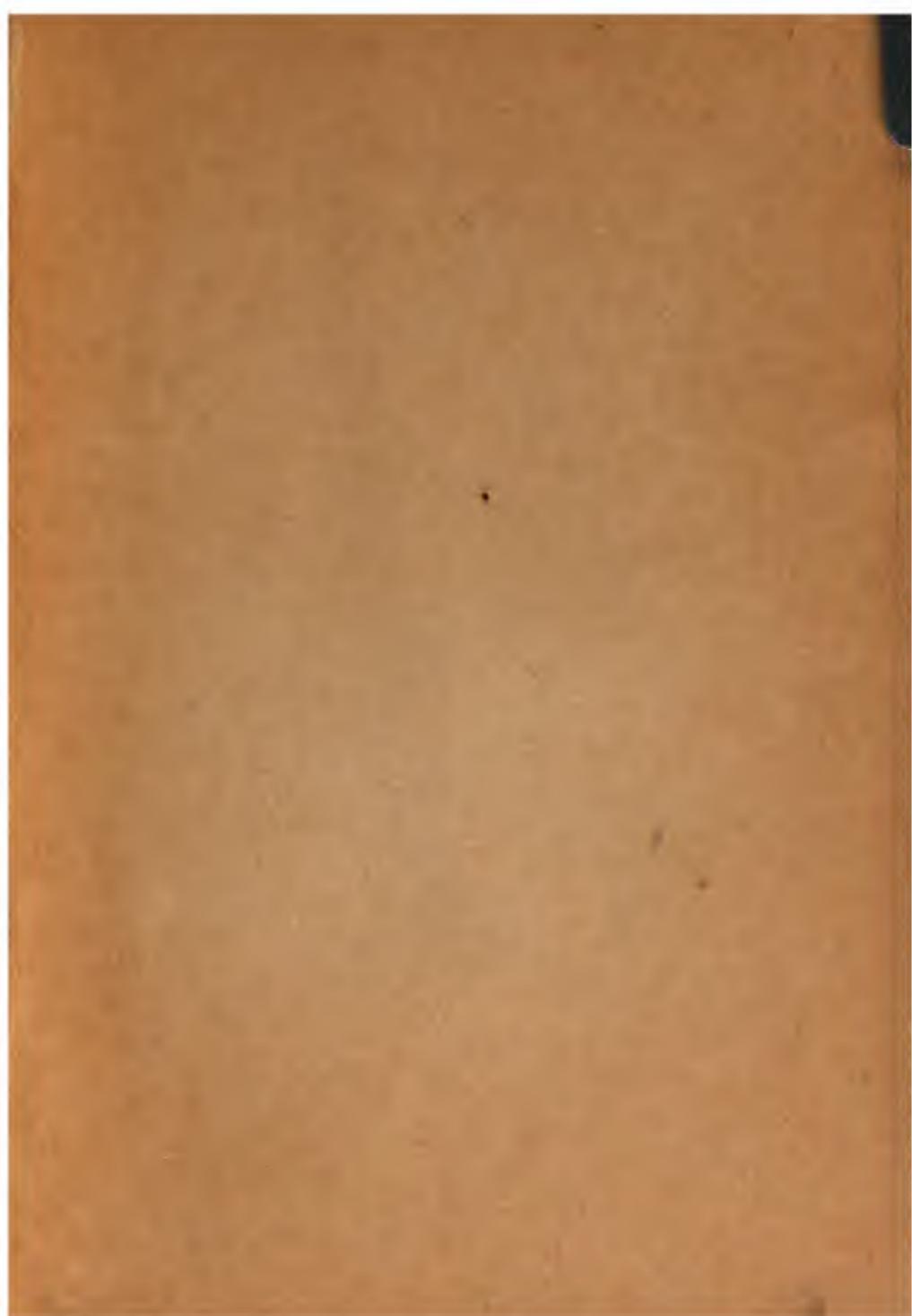
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